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(54) Filters utilizing thin film stacked crystal filter structures and thin film bulk acoustic wav resonators

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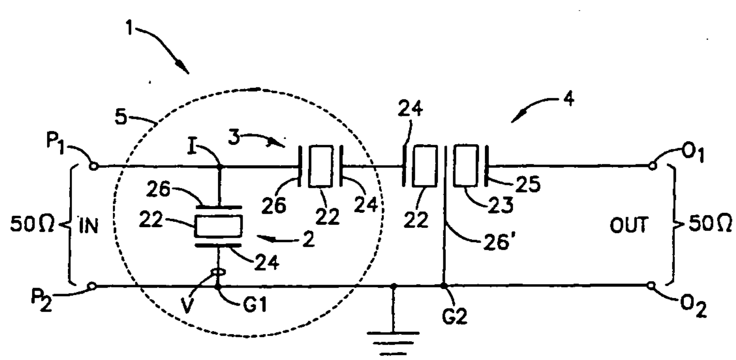

FIG.10a

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EUROPEAN SEARCH REPORT

Application Number
EP 98 30 4059

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
D,A	LAKIN K M ET AL: "Thin film bulk acoustic wave filters for GPS" IEEE 1992 ULTRASONICS SYMPOSIUM (CAT. NO.92CH3118-7), TUCSON, AZ, USA, 20-23 OCT. 1992, pages 471-476 vol.1, XP002130402 1992, New York, NY, USA, IEEE, USA ISBN: 0-7803-0562-0 * page 471, left-hand column, line 16 - right-hand column, line 3 * * paragraph [00II] * * figure 1 * ---	1,12,13, 16,20,24	H03H9/58
D,A	DRISCOLL M M ET AL: "RECENT ADVANCES IN MONOLITHIC FILM RESONATOR TECHNOLOGY" PROCEEDINGS OF THE ULTRASONICS SYMPOSIUM,US,NEW YORK, IEEE, vol. -, 1986, pages 365-369, XP000647236 * page 366, right-hand column, line 30 - page 367, right-hand column, line 9; figure 3 * ---	1,12,13, 16,20,24	TECHNICAL FIELDS SEARCHED (Int.Cl.6)
D,A	US 5 382 930 A (STOKES ROBERT B ET AL) 17 January 1995 (1995-01-17) * column 4, line 12 - line 52; figure 3 * ---	1,12,13, 16,20,24	H03H
A	KRISHNASWAMY S V: "FILM BULK ACOUSTIC WAVE RESONATOR AND FILTER TECHNOLOGY" INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST (MTT-S),US,NEW YORK, IEEE, vol. -, 1992, pages 153-155, XP000332705 * page 154, left-hand column, line 64 - page 155, left-hand column, line 22 * -----	1,12,13, 16,20,24	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	18 February 2000	D/L PINTA BALLE.., L

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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(54) Filters utilizing thin film stacked crystal filter structures and thin film bulk acoustic wav resonators

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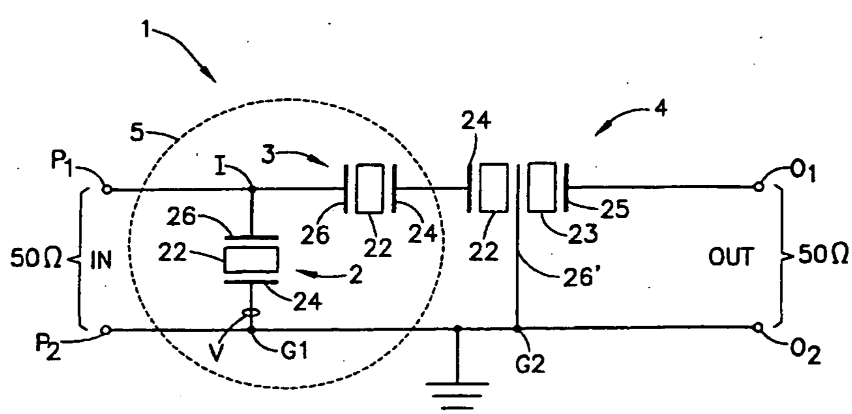

FIG.10a

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can be achieved during the fabrication of the devices. By example, in a case in which the BAW resonators include one or more membrane layers, an additional layer of suitable material and thickness may be added to the membrane layers of the shunt-connected devices during fabrication so that, after the devices are completely fabricated, the shunt-connected devices will have thicker layer stacks than the series-connected resonators. As another example, the series resonators can be fabricated to have thinner piezoelectric layers than the shunt resonators, and/or the thicknesses of the upper electrodes of the series resonators can be reduced by a selected amount using a suitable technique, after the deposition of the upper electrode layers. These steps require the use of masking layers.

The performance of BAW ladder filters may be further understood in view of the element equivalent circuit of the BAW resonator shown in Fig. 4b. The series resonance of the individual BAW resonator is caused by the equivalent inductance (Lm) and the equivalent capacitance (Cm). At the series resonant frequency of the BAW resonator, the impedance of the BAW resonator is low (i.e., in an ideal case, where there are no losses in the device, the BAW resonator functions like a short circuit). At frequencies that are lower than this series resonant frequency, the impedance of the BAW resonator is capacitive. At frequencies that are higher than the series resonant frequency of the BAW resonator, but which are lower than the parallel resonant frequency of the device (the parallel resonance results from equivalent capacitance (Co)), the impedance of the BAW resonator is inductive. Also, at higher frequencies than th parallel resonant frequency of the BAW resonator, the impedance of the device is again capacitive, and, at the parallel resonant frequency of the device, the impedance of the BAW resonator is high (i.e., in an ideal case the impedance is infinite and the device resembles an open circuit at the parallel resonant frequency).

For an exemplary case in which two BAW resonators (e.g., a shunt BAW resonator and a series BAW resonator) having equivalent circuits similar to the one shown in Fig. 4b are employed in a BAW ladder filter, a lowest resonant frequency of the filter is one at which the series resonance of the shunt BAW resonator occurs. At this frequency, an input of the BAW ladder filter is effectively shorted to ground, and thus a frequency response of the BAW ladder filter exhibits a deep notch below the passband of the filter. The next highest resonant frequencies of the BAW ladder filter are the series resonant frequency of the series BAW resonator and the parallel resonant frequency of the shunt BAW resonator. These resonant frequencies are within the passband frequencies of the BAW ladder filter, and are located at or near the desired center frequency of the BAW ladder filter on the frequency spectrum. At the parallel resonant frequency of the shunt BAW resonator, the shunt BAW resonator behaves like an open circuit, and at the series resonant frequency of the series BAW resonator, the series BAW resonator behaves like a short circuit (and thus provides a low-loss connection between input and output ports of the BAW ladder filter). As a result, for a case in which a signal having a frequency that is approximately equal to the center frequency of the BAW ladder filter is applied to the input of the BAW ladder filter, the signal experiences minimum insertion loss (i.e., it encounters low losses) as it traverses the filter circuit between the filter's input and output.

A highest resonant frequency of the BAW ladder filter is one at which the series-connected BAW resonator yields a parallel resonance. At this frequency, the series BAW resonator behaves like an open circuit and the shunt BAW resonator behaves like a capacitor. As a result, the filter's input and output are effectively de-coupled from one another, and the frequency response of the filter includes a deep notch above the filter's passband.

The frequency response of a BAW ladder filter that includes no tuning elements typically has deep notches and steeply-sloped upper and lower passband edges (i.e., skirts). Unfortunately, however, these types of ladder filters tend to provide poor stopband attenuation (i.e., out-of-band rejection) characteristics. An example of a measured frequency response of a BAW ladder filter that exhibits deep notches, steeply-sloped passband edges, and poor stopband attenuation, and which includes four BAW resonators and no tuning elements, is shown in Fig. 9a.

Another exemplary frequency response is shown in Fig. 8e, for the BAW ladder filter 41 of Fig. 8d. The BAW ladder filter 41 yields the frequency response of Fig. 8e assuming that 1) the resonators 43 and 42 include the layers listed in respective Tables 1 and 2 below, 2) the layers of resonators 43 and 42 have thicknesses and include the materials listed in respective Tables 1 and 2, 3) the filter 41 is connected between 50 Ohm terminals, and 4) the filter 41 includes no tuning elements.

SERIES BAW RESONATOR (43, 45) Layer		SHUNT BAW RESONATOR (42, 46) Layer	
	m		

As can be appreciated in view of Tables 1 and 2, the BAW resonator 42 includes two membrane layers, and th BAW resonator 43 includes only a single membrane layer. The employment of two membrane layers in the resonator 42 causes the resonant frequencies yielded by the resonator 42 to be lower than those yielded by the series-connected resonator 43, as was described above.

The level of stopband attenuation provided by a BAW ladder filter can be increased by including additional BAW resonators in the filter and/or by constructing the filter so that the ratio of the areas of the filter's parallel-connected BAW resonators to the areas of the filter's series-connected BAW resonators is increased. Fig. 8g shows an exemplary "simulated" frequency response of the filter 44 (which includes a greater number of resonators than the filter 41), assuming that 1) the resonators 43 and 45 include the layers having the thicknesses and materials listed in Table 1, 2) the resonators 42 and 46 include the layers having the thicknesses and materials listed in Table 2, and 3) the filter 44 includes no tuning elements.

As can be appreciated in view of Figs. 8e and 8g, the degree of attenuation provided by the filter 44 at out-of-band frequencies is improved somewhat over the attenuation level provided by the filter 41 that includes only two BAW resonators. Unfortunately, however, the employment of additional BAW resonators in a filter increases the filter's overall size and can cause an undesirable increase in the level of insertion loss of the filter. This is also true in cases in which the filter's parallel-connected BAW resonators are fabricated to have larger areas than the series-resonators. Moreover, even if such measures are taken in an attempt to improve the filter's passband response, the level of stopband attenuation provided by the filter may be insufficient for certain applications.

As shown in Figs. 8e and 8g, the center frequencies of the passbands of respective filters 41 and 44 are located at about 947.5 MHz on the frequency spectrum, and the minimum passband bandwidth yielded by each of the filters 41 and 44 is approximately 25 MHz. As can be appreciated by those having skill in the art, these frequency respons characteristics are required of filters that are employed in GSM receivers.

It is known to employ one or more SCF devices in a passband filter. An advantage of employing SCF devices in passband filters is the better stopband attenuation characteristics provided by these filters in general, as compared to the stopband attenuation characteristics of typical BAW ladder filters. An exemplary lumped element equivalent circuit of a SCF is shown in Fig. 8b. The equivalent circuit includes an equivalent inductance (2Lm), an equivalent capacitance (Cm/2), an equivalent resistance (2R), and parasitic capacitances (Co). As can be appreciated in view of Fig. 8b, the SCF can be considered to be an LC resonator having parallel capacitances (Co) connected to ground.

Like the BAW ladder filters described above, filters that are comprised primarily of SCF devices can also suffer from a number of drawbacks. One drawback is that SCFs generally yield frequency responses that do not exhibit such desired characteristics as deep notches and steeply-sloped passband edges. This can be seen in view Fig. 8c, which shows an exemplary frequency response of a SCF. The frequency response of a filter that is comprised primarily of one or more SCF components can be improved to some extent by connecting an inductor between each SCF structure, as is described in U.S. Patent No. 5,382,930. Unfortunately, however, the addition of these inductors adds to the overall size and complexity of the filter, and can also increase the filter's level of insertion loss, owing to losses in the inductors. Another drawback associated with these types of filters is that it can be difficult to control the passband bandwidths of the filters.

In view of the above description, it can be appreciated that it would be desirable to provide a filter which can yield the desired frequency response characteristics provided by both BAW ladder filters and Stacked Crystal Filters. That is, it would be desirable to provide a filter which exhibits a frequency response having deep notches and steeply-sloped upper and lower passband edges, and which also yields stopband attenuation levels that are similar to those generally yielded by Stacked Crystal Filters. It is also desirable that the filter be small in size, and be able to exhibit the desired frequency response characteristics without the use of tuning elements.

in series in the s cond lead, and which has a first terminal coupled to a third one of the ports. The balanced BAWR-SCF circuit further comprises a sixth BAW resonator that is connected in series in the second lead, and which includes a first terminal that is coupled to a fourth one of the ports. The BAWR-SCF in accordance with this embodiment of the invention further comprises an additional SCF. This SCF includes first, second, and third terminals. The first terminal is coupled to a s cond terminal of the fifth BAW resonator, the second terminal is coupled to a second terminal of the sixth BAW resonator, and the third terminal is connected to the node.

In accordance with the invention, by employing the BAW resonators connected in a ladder topology and SCFs within a single circuit, such as any one of the various embodiments of the BAWR-SCF circuit described above, the desired characteristics provided by both BAW ladder filters and Stacked Crystal Filters can be provided. Each of the various embodiments of the BAWR-SCF circuit described above exhibits a frequency response having deep notch s and steeply-sloped passband edges that are similar to those typically yielded by BAW ladder filters, and also yields stopband attenuation characteristics that are similar to those typically yielded by Stacked Crystal Filters. The BAWR-SCF circuits of the invention provide generally improved frequency responses relative to those that can be exhibit d by, for example, individual BAW ladder filters or individual SCF devices.

In each of the BAWR-SCF devices of the invention, 'series-connected' ones of the BAW resonators preferably include layer stacks of similar thicknesses, and 'parallel-connected' (or 'shunt-connected') ones of the BAW resonators preferably include layer stacks of similar thicknesses. Preferably, the series-connected BAW resonators include thinner layer stacks than do the parallel-connected BAW resonators, thereby enabling each BAWR-SCF device to yield a frequency response having an upper notch at the frequency of the parallel resonances of the series-connected BAW resonators, and a lower notch at the frequency of the series resonances of the parallel-connected BAW resonators.

In accordance with another aspect of the invention, each SCF (which yield series resonances) of the BAWR-SCF circuits may be fabricated to have a layer stack of a thickness that enables the SCF to yield either a fundamental resonant frequency or a second harmonic resonant frequency at or near the desired ('design') center frequency of th BAWR-SCF device. Preferably, the BAWR-SCF devices of the invention are constructed so that the SCFs yield a second harmonic resonance, rather than a fundamental resonance, at the 'design' center frequency of the respectiv BAWR-SCF devices. This is because the BAWR-SCF devices are easier to fabricate in this case.

The BAWR-SCF circuits may include any suitable types of BAW resonators and SCFs, including, for example, solidly-mounted (i.e., acoustic mirror structure) BAW resonators and SCFs. The use of acoustic mirrors in the BAWR-SCF devices offers a number of advantages over the use of other types of structures. One advantage is that the acoustic mirror devices are structurally more rugged than the other types of devices. Another advantage is that, in high power applications, any heat that may be generated due to losses in the devices is conducted efficiently to the substrates of the respective devices via the acoustic mirrors. A further advantage of using acoustic mirror devices in the BAWR-SCF devices of the invention is that the acoustic mirrors can help to attenuate any unwanted harmonic responses that may occur in the devices.

In accordance with another aspect of the invention, it is preferable that each of the BAWR-SCF devices of the invention be constructed so as to include as few vias as possible in the structures of the respective devices.

In accordance with another aspect of the invention, a duplex filter (duplexer) for use in a transceiver is provided. The duplex filter preferably comprises a first, 'transmit' portion and a second, 'receive' portion. During times when the duplexer is connected within a transceiver, the first portion filters signals that are output by a transmitter portion of th transceiver before the signals are transmitted from the transceiver over an antenna. The second portion of the duplexer filters signals that are received by the antenna, and provides filtered signals to a receiver portion of the transceiver. The first and second portions of the duplexer each comprise a respective BAWR-SCF circuit, which may be similar to any of those described above. Preferably, the first portion of the duplexer is tuned to yield a passband response having a center frequency f_{c1}, a lower notch at a frequency f_{N1}, and an upper notch at a frequency f_{N2}, and the second portion of the duplexer is tuned to yield a passband response having a center frequency f_{c2}, a lower notch at a frequency f_{N3}, and an upper notch at a frequency f_{N4}.

In accordance with a further aspect of the invention, a double duplex filter for use in a dual-mode transceiving device (e.g., a dual-mode mobile station) is provided. The double duplex filter preferably comprises a first duplexer and a second duplexer. In accordance with a preferred embodiment of the invention, the first duplexer includes a first filter and a second filter. Each of the first and second filters has a respective first pair of ports coupled to an output of a transmitter portion of the transceiving device, and each of the first and second filters also includes a respective second pair of ports. At least a first one of the second pair of ports of each of the first and second filters is coupled to at least one antenna of the transceiving device. The first and second filters comprise respective BAWR-SCF circuits that are tuned to provide passbands over a first frequency band and a second frequency band, respectively.

The second duplexer of the double duplex filter preferably also includes a first filter and a second filter. Each of these duplex filters has a respective first pair of ports and a respective second pair of ports. At least a first one of the first pair of ports of each filter is coupled to the at least one antenna. The second pair of ports of the filters are preferably coupled to an input of a receiver portion of the transceiving device. The first and second filters of the second duplex r

Fig. 9b shows a piezoelectric layer 22 of a BAW resonator (A), and a pair of piezoelectric layers 22 and 23 of a SCF (B), wherein the piezoelectric layer 22 of BAW resonator (A) has a thickness of T, and wherein each piezoelectric layer 22 and 23 of BAW resonator (B) has a thickness of T/2;

Fig. 9c shows an exemplary frequency response (A') of a filter that includes BAW r sonators connected in a ladder configuration, wherein the BAW resonators of the filter include the piezoelectric layer 22 of Fig. 9b; Fig. 9c also shows an exemplary frequency response (B') of a SCF that includes the piezoelectric layers 22 and 23 of Fig. 9b;

Fig. 9d shows the piezoelectric layer 22 of the BAW resonator (A) of Fig. 9b, and also shows a pair of piezoelectric layers 22 and 23 of a SCF (B1), wherein the piezoelectric layer 22 of BAW resonator (A) and the piezoelectric layers 22 and 23 of SCF (B1) each have respective thicknesses of T;

Fig. 9e shows a portion of the exemplary frequency response (A') of Fig. 9c, and also shows an exemplary frequency response (C') of a SCF that includes the piezoelectric layers 22 and 23 of Fig. 9d;

Fig. 9f shows the BAW ladder filter of Fig. 8f having a topology that requires a via (V) to be provided in the filter;

Fig. 9g shows the BAW ladder filter of Fig. 8f having a topology that requires vias (V1), (V2) and (V3) to be provided in the filter;

Fig. 9h shows the balanced filter of Fig. 8i having a topology that requires vias (V1) and (V2) to be provided in the filter;

Fig. 9i shows a cross section of an exemplary BAW resonator structure;

Fig. 9j shows a cross section of the BAW resonator structure of Fig. 9i, taken along line 9j-9j of Fig. 9i, wherein a via (V) is included in the BAW resonator structure;

Fig. 10a illustrates a circuit diagram of a Bulk Acoustic Wave Resonator-Stacked Crystal Filter (BAWR-SCF) devic that is constructed in accordance with an embodiment of the invention, and which has a basic topology;

Fig. 10b shows a frequency response of the BAWR-SCF device of Fig. 10a;

Fig. 10c shows the frequency response of Fig. 10b superimposed over the frequency responses of Figs. 8e and 8c;

Fig. 10d shows a circuit diagram of a BAWR-SCF device that is constructed in accordance with another embodiment of the invention;

Fig. 10e shows a lumped element equivalent circuit of the device of Fig. 10d;

Fig. 10f shows a frequency response (FR) of a SCF of the BAWR-SCF device of Fig. 10a;

Fig. 10g shows a frequency response (FR1) of a BAW ladder filter portion of the BAWR-SCF device of Fig. 10a superimposed over the frequency response (FR) of Fig. 10f;

Fig. 10h shows a frequency response 106 of the BAWR-SCF device of Fig. 10d superimposed over the frequency response of Fig. 10b and a frequency response 108 of an exemplary "inverted" BAW ladder filter;

Fig. 11a shows a BAWR-SCF device that is constructed in accordance with a another embodiment of the invention;

Fig. 11b shows a frequency response of the device of Fig. 11a;

Fig. 11c shows a circuit diagram of a BAWR-SCF device that is constructed in accordance with a further embodiment of the invention;

Fig. 12 shows a circuit diagram of a balanced BAWR-SCF device that is constructed in accordance with an embodiment of the invention;

the acoustic mirror 70 and the electrode 24, if needed to tune the device 23a to enable it to provide desired frequency response characteristics.

The acoustic mirror 70 may comprise an odd number of layers (e.g., from three to nine layers). The acoustic mirror 70 shown in Fig. 3a comprises three layers, namely a top layer 70a, a middle layer 70b, and a bottom layer 70c. Each layer 70a, 70b and 70c has a thickness that is, by example, approximately equal to one quarter wavel ngth at the center frequency of the device. The top layer 70a and bottom layer 70c are comprised of materials having low acoustic impedances such as, by example, silicon (Si), silicon-dioxide (SiO2), poly-silicon, aluminum (Al), or a polymer. Also, the middle layer 70b is comprised of a material having a high acoustic impedance such as, by example, gold (Au), molybdenum (Mo), or tungsten (W) (tungsten is preferred). A ratio of the acoustic impedances of consecutive layers is large enough to permit the impedance of the substrate to be transformed to a lower value. When the piezoelectric layer 22 vibrates, the vibrations it produces are substantially isolated from the substrate 36 by the layers 70a, 70b and 70c. Being that the vibrations are isolated in this manner, and because no etching of the substrate 36 is required during the fabrication the BAW resonator 23, the substrate 36 may be comprised of various materials having low or high acoustic impedances such as, by example, Si, SiO_2, GaAs, glass, or a ceramic material (e.g., alumina). Also, for any of the high impedance dielectric layers described above, tantalum dioxide may be employed in lieu of the materials mentioned above.

In Fig. 4a, a cross-section of another type of BAW resonator 80 is shown. The resonator 80 comprises a piezoelectric layer 22, a first, lower electrode 24, a second, upper electrode 26, a membrane 88, and a substrate 90 having a via 92. The piezoelectric layer 22, the first and second electrodes 24 and 26, and the membrane 88 form a stack that preferably has a thickness of, by example, 2 μm to 10 μm, and the substrate 90 preferably has a thickness of, by example, 0.3 mm to 1 mm. A portion of the via 92 located directly underneath the membrane 88 preferably has a length of, by example, 100 μm to 400 μm. The substrate 90 may comprise, by example, Si or GaAs. The resonator 80 functions in a similar manner as the resonator 20 described above in that both of these devices employ air interfaces to reflect acoustic vibrations produced by the piezoelectric layers 22 of the respective devices. A primary difference between these resonators 20 and 80, however, is the method employed for fabricating the respective devices. For example, for the resonator 80, after all of the layers 22, 24, 26, and 88 are formed, a portion of the substrate is then etched away from underneath the substrate 90 to form the via 92.

Each of the BAW resonators described above may be fabricated using thin film technology, including, by example, sputtering and chemical vapor deposition steps. BAW resonators exhibit series and parallel resonances that are similar to those of, by example, crystal resonators. Resonant frequencies of BAW resonators can typically range from about 0.5GHz to 5GHz, depending on the layer thicknesses of the devices. Also, the impedance levels of BAW resonators are a function of the horizontal dimensions of the devices.

Reference will now be made to Figs. 5a-8a, which show various embodiments of another type of BAW device, namely a Stacked Crystal Filter (SCF). Figs. 5a and 5b show a Stacked Crystal Filter 20'. The SCF 20' is constructed of layers 36, 32, 30, 24, 22, 38a, and 38b, an air gap 34, and etch windows 40a and 40b, that are similar to those of the BAW resonator 20 described above. In addition to these layers, the Stacked Crystal Filter 20' also includes a second, middle electrode 26', which is similar to the electrode 26 of the BAW resonator 20 described above, and which is employed as a ground electrode. The SCF 20' also includes an additional piezoelectric layer 23 that is disposed over the electrode 26' and over portions of the piezoelectric layer 22. The SCF 20' further includes a third, upper electrode 25 that is disposed over a top portion of the piezoelectric layer 23. The electrodes 25 and 26' may comprise similar materials as the electrodes 24 and 26 of BAW resonator 20, and the piezoelectric layers 22 and 23 may comprise similar materials as the piezoelectric layer 22 of BAW resonator 20. Also, as can be appreciated in view of Figs. 5a and 5b, the protective layer 38a covers portions of the piezoelectric layer 23 and the electrode 25, in addition to cov ring portions of the other layers of the SCF 20'. For the purposes of this description, the piezoelectric layers 22 and 23 of SCF 20' are also referred to as a first, lower piezoelectric layer 22, and a second, upper piezoelectric layer 23, respectively.

Fig. 6 shows a Stacked Crystal Filter 21' that is similar to that of Figs. 5a and 5b, with an addition of a sacrificial layer 39. The sacrificial layer 39 is employed to form an air gap (not shown in Fig. 6) in a similar manner as was described above with respect to Fig. 2. The layer 32 provides protection for the piezoelectric layer 22 during the removal of the sacrificial layer 39.

Fig. 7a shows a solidly-mounted Stacked Crystal Filter 23' that comprises layers 36, 70, 70a, 70b, 70c, 24, 22, and 38a, that are similar to those of BAW resonator 23a of Figs. 3a and 3b. The SCF 23' also includes an additional piezoelectric layer 23, a second, middle electrode 26', and a third, upper electrode 25. The electrodes 25 and 26' may comprise similar materials as the electrodes 24 and 26 of BAW resonator 23a, and the piezoelectric layers 22 and 23 may comprise similar materials as the piezoelectric layer 22 of BAW resonator 23a. The piezoelectric layer 23 is disposed over portions of the electrode 26' and the piezoelectric layer 22, and the electrod 25 is disposed over a top surface of the piezoelectric layer 23. The electrode 26' of SCF 23' serves as a ground electrode and covers portions of the acoustic mirror 70 and the piezoelectric layer 22. Protective layer 38a covers portions of the layers 23, 25, and

BAWR-SCF devices to be described below, the "series-connected" BAW resonators preferably have thinner layer stacks than do th "parallel-connected" BAW resonators, thereby enabling the BAWR-SCF devices to yield a passband having an upp r notch at the frequency of the parallel resonances of the series-connected BAW resonators, and a lower notch at the frequency of the series resonances of the parallel-connected BAW resonators.

Each series-connected BAW resonator of each BAWR-SCF circuit preferably has a layer stack having a thickness that is similar to that of the layer stacks of the other series-connected BAW resonators (if any) included in the BAWR-SCF circuit. Similarly, each parallel-connected BAW resonator of each BAWR-SCF circuit preferably has a layer stack having a thickness that is similar to that of the layer stacks of the other parallel-connected BAW resonators (if any) included in the BAWR-SCF circuit. The manner in which the particular thicknesses of the BAW resonator layer stacks are chosen to yield the desired frequency response characteristics (e.g., the desired center frequency, passband bandwidth, level of insertion loss, level of out-of-band rejection, passband ripple amplitude, notch depths, passband edge slopes, etc.) may be in accordance with any suitable technique. As such, aspects relating to the design of the BAW resonators of the BAWR-SCF devices to be described below will not be further described below in the descriptions of all of the devices.

In accordance with another aspect of the invention, the SCFs of each BAWR-SCF circuit may be fabricated to have layer stacks of thicknesses that enable the SCFs to yield either a fundamental (series) resonant frequency or a second harmonic (series) resonant frequency at or near the "design" center frequency of the BAWR-SCF circuit. As can be appreciated, the layer stack thicknesses of the SCFs will differ in each case. This difference in layer stack thicknesses is preferably provided by a difference in the thicknesses of the piezoelectric layers of the stacks, although the difference may also be provided by differences in the thicknesses of the remaining layers of the stacks. Which one of these "layer differences" is employed, however, may depend on various considerations, such as applicable design requirements, the relative ease of device fabrication for each case (e.g., it is preferred that device fabrication be as simple as possible), etc. By example, in cases in which ease of device fabrication is a concem, it is preferable that the "difference" in the layer stack thicknesses be provided by a "difference" in the piezoelectric layers, and that the upper, middle, and lower electrodes of the SCF devices of each BAWR-SCF circuit have similar thicknesses as each electrode of the BAW resonators of the BAWR-SCF device, since this allows for simplified device fabrication (as will be further described below). However, it should be noted that, in practice, design, manufacturing, and/or other requirements, as well as possible imperfections in the fabrication process, may make it necessary to fabricate the SCF devices so that at least one of the electrodes of each SCF has a different thickness than the electrodes of the BAW resonators, as will be further described below. It should also be noted that, in cases in which the series and shunt BAW resonators are constructed to include membrane layers, it is preferred that the SCFs also be constructed to include membrane layers. For cases in which the shunt BAW resonators include thicker membrane layers than the series BAW resonators (to provide the upper and lower passband notches), the SCFs may be constructed to include a membrane layer having a thickness that is similar to the membranes of either the series or shunt BAW resonators, depending on, for example, applicable design criteria and fabrication techniques employed (e.g., it is preferred that the fabrication process be as simple as possible). Moreover, in cases in which the shunt BAW resonators are constructed to include a membrane layer, and where the series BAW resonators are constructed so as to not include a membrane layer, the SCFs may be constructed to either include or not include a membrane layer, depending on, for example, applicable design criteria and fabrication techniques employed (e.g., it is preferred that fabrication be as simple as possible). In either of these cases, and as was described above, the SCFs of each BAWR-SCF circuit are fabricated to have overall layer stack thicknesses that enable the SCFs to yield either a fundamental (series) resonant frequency or a second harmonic (series) resonant frequency at or near the "design" center frequency of the BAWR-SCF circuit.

The relationship between the thicknesses of the piezoelectric layers of SCFs and BAW resonators of a BAWR-SCF circuit, with regard to whether the SCF yields a fundamental resonance or a second harmonic resonance at the center frequency of the BAWR-SCF circuit, may be further understood in view of Figs. 9b-9e.

Fig. 9b illustrates a piezoelectric layer 22 of a layer stack of an individual BAW resonator (A) (for convenience, the other layers of resonator (A) are not shown), and a piezoelectric layers 22 and 23 of a layer stack of an individual SCF (B) (for convenience, the other layers of SCF (B) are not shown), for a case in which the layer 22 of the BAW resonator (A) has a thickness of (T), and the layers 22 and 23 of the SCF (B) each have respective thicknesses of (T/2). Fig. 9c shows an exemplary frequency response (A') of a BAW ladder filter, assuming that BAW resonators of the ladder filter each include a piezoelectric layer having a thickness of (T). The frequency response (A') has a center frequency (f_1). Also, the individual SCF (B) having the piezoelectric layers 22 and 23 of Fig. 9b yields a frequency response (B') and a fundamental resonant frequency of (f_1).

Fig. 9d illustrates the piezoelectric layer 22 of the individual BAW resonator (A), and piezoelectric layers 22 and 23 of an individual SCF (B1), for a case in which the layer 22 of the BAW resonator (A), and the layers 22 and 23 of the SCF (B1) each have respective thicknesses of (T). The SCF (B1) yields a frequency response (C') having a second harmonic resonance at the frequency (f_1), and a fundamental resonance at the frequency ($f_{1/2}$), as shown in Fig. 9e. A portion of the frequency response (A') is also shown in Fig. 9e, wherein the passband is centered at frequency (f_1).

may need to be optimized for enabling the SCFs to yield the desired resonant frequency. By example, assuming that applicable design criteria require that the electrodes of the SCFs be very thick relative to the BAW resonator electrod thicknesses, and that this would cause the SCFs to yield a second harmonic resonant frequency that is offset from th desired BAWR-SCF circuit center frequency by an unacceptable large frequency differ ntial, the thickn ss of one of the piezoelectric layers and/or the membrane layers can be optimized (e.g., reduced) to enabl the SCFs to provide the desired resonant frequency.

The BAWR-SCF circuits to be described below may be fabricated as monolithic integrated circuits or may be fabricated to include BAW resonator and SCF components formed on separate respective wafers. Also, and as was described above, the BAWR-SCF circuits to be described below may include any of the various types of BAW resonators described above and shown in Figs. 1a-4a, and any of the various types of SCFs described above and shown in Figs. 5a-8a. For example, each BAW resonator and SCF may include "bridge" structures (i.e., one or more membrane layers) like the BAW resonator 20 of Fig. 1a and the SCF 20' of Fig. 5a. Also by example, each BAW resonator and SCF may be a solidly-mounted device (a device that includes an acoustic mirror) similar to the ones shown in Figs. 3a and 7a, respectively. If acoustic mirror devices are employed, the shunt BAW resonators of the respective BAWR-SCF circuit preferably include a membrane layer between the top acoustic mirror layer and the lower electrode layer to enable the shunt BAW resonators to provide a notch below the BAWR-SCF circuit's passband, in the manner described above.

The use of acoustic mirror devices in the BAWR-SCF circuits offers a number of advantages over the use of other types of devices such as, by example, those that include bridge structure, in the BAWR-SCF circuits. One advantage is that the acoustic mirror devices are structurally more rugged than the other types of devices. Another advantage is that, in high power applications, any heat that may be generated due to losses in the devices is conducted efficiently to the substrates of the respective devices via the acoustic mirrors.

A further advantage of using acoustic mirror devices in the BAWR-SCF circuits of the invention is that the acoustic mirrors can help to attenuate any unwanted harmonic responses that may be produced within the BAWR-SCF devices. This may be further understood in view of the following example. In this example, it is assumed that in the BAWR-SCF devices described below, the piezoelectric layers of each SCF each have a thickness that is equal to the thickness of the individual piezoelectric layer of the respective BAW resonators, and that, as a result, each SCF exhibits a second harmonic resonance at a center frequency of the BAWR-SCF device. It is also assumed that the BAW resonators and the SCFs of the BAWR-SCF devices include acoustic mirror layers, and that each acoustic mirror layer has a thickness of one-quarter wavelength (e.g., $\lambda/4$) at the center frequency of the respective BAWR-SCF device. In this case, each SCF exhibits a fundamental resonance at a frequency which is approximately equal to one-half of the center frequency of the BAWR-SCF device, and thus may cause a spurious response at this frequency. At the fundamental resonant frequency of the SCF, the thickness of each acoustic mirror layer is $\lambda/8$. As can be appreciated by those skilled in the art, at this frequency the amount of acoustic energy which is reflected back towards the bottom piezoelectric layer of the SCF by the interface between the top layer of the acoustic mirror and the lower electrode of the SCF is small. As a result, the spurious response of the SCF at its fundamental resonant frequency becomes attenuated. In cases in which the BAWR-SCF circuit includes "bridge" type structures instead of acoustic mirror structures, external matching circuitry may be employed to attenuate any spurious responses that may occur at the fundamental resonant frequency of the SCF, although at least some attenuation is also provided by the BAW resonators of the BAWR-SCF device.

As another example, it is assumed that each piezoelectric layer of the SCF has a thickness which is equal to one-half of the thickness of each individual piezoelectric layer of the BAW resonators, and that, as a result, the SCF exhibits a fundamental resonance at the center frequency of the BAWR-SCF circuit. In this case, harmonic resonances of th SCF and the BAW resonators of the BAWR-SCF circuit may cause spurious responses, although no spurious responses can occur at frequencies that are lower than the BAWR-SCF circuit's center frequency. By example, spurious responses may occur at the second harmonic resonant frequencies of the SCF and the BAW resonators. At the second harmonic resonant frequency of the SCF, the acoustic mirror layers of the SCF have a thickness which is equal to $\lambda/2$ and no impedance transformation of the substrate of the device occurs at the interface between the top acoustic mirror layer and the lower electrode. As a result, acoustic energy is not reflected by this interface away from the substrate and back towards the piezoelectric layers, but is instead propagated to the substrate. This causes the spurious respons of the SCF at its second harmonic resonant frequency to become attenuated.

Another consideration relating to the fabrication of the BAWR-SCF devices of the invention will now be described. Thin film devices that include BAW components (e.g., BAW resonators or SCFs) often include one or more vias. At least one of these vias may be employed to contain an electrically conductive material for enabling a lower or middle electrode of one BAW component to be electrically coupled to another component such as, for example, an upper electrode of another resonator of the device, an external circuit (e.g., bonding wires coupled to a wiring substrate), or a contact pad or terminal (also referred to as a node) of the device. In some cases, it may not be required to provide these vias if the BAW components are coupled to one another through their upper electrodes or through their lower electrodes, or in cases in which a BAW component is coupled to, for example, an external circuit or contact pad, through the component's upper electrode.

frequency of the BAWR-SCF circuit 1, which is also the center frequency of the L segment 5. Further in accordance with the above description, the devices 2, 3, and 4 are preferably constructed so that the SCF 4 exhibits a second harmonic resonance at approximately the center frequency of the device 1 (i.e., at approximately the center frequency of the L segment 5).

Fig. 10b shows a frequency response of the BAWR-SCF circuit 1, for an exemplary case in which 1) the device 1 is constructed so as to yield a passband having a bandwidth of approximately 25 MHz and a center frequency of about 947.5 MHz, 2) the ports (P1) and (P2) of the device 1 are 50 ohm ports, 3) the ports (O1) and (O2) of the device 1 are 50 ohm ports, and 4) the individual BAW resonators 2 and 3 and the SCF 4 include layers having the thicknesses shown in Tables 3, 4, and 5, respectively. As can appreciated in view of the exemplary dimensions shown in these Tables, each of the lower and upper piezoelectric layers 22 and 23 of the SCF 4 has a thickness which is equal to the thickness of the piezoelectric layer 22 of each of the BAW resonators 2 and 3, and the middle electrode (ground electrode) 26' of the SCF 4 has a thickness of 520 nm. Having these thicknesses, the SCF 4 exhibits a second harmonic frequency at the center frequency of the BAWR-SCF circuit 1. This can be further understood in view of Figs. 10f and 10g. Fig. 10f shows a frequency response (FR) of the SCF 4 alone. Having the layer dimensions shown in Table 5, the SCF 4 yields a fundamental resonance at approximately 511 MHz, and a second harmonic resonance at approximately 947.5 MHz. In Fig. 10g, a frequency response (FR1) of the ladder configuration (L segment 5) of BAW resonators 2 and 3 is shown superimposed over the frequency response (FR) of the SCF 4. As can be seen in view of Fig. 10g, the resonant frequency of the SCF 4 is similar to the center frequency of the ladder configuration (L segment 5) of BAW resonators 2 and 3

The BAWR-SCF device 1 exhibits an improved frequency response over those yield d by, for example, the individual ladder filter 41 of Fig. 8d (which, unlike the BAWR-SCF device 1, does not include an SCF 4), or an individual SCF. This can be seen in view of Fig. 10c, which shows the frequency response 1' of the BAWR-SCF circuit 1 overlapped with the frequency response 41' of the filter 41 of Fig. 8d and the frequency response 4a' of the individual SCF 4. As can be appreciated in view of Fig. 10c, the BAW resonators 2 and 3 of the BAWR-SCF circuit 1 enable the frequency response 1' to have steeply-sloped upper and lower passband edges, and deep notches above and below the passband. Also, the SCF 4 enables the device 1 to exhibit greater stopband attenuation (e.g., out-of-band rejection) than is yielded by, for example, the ladder filter 41 of Fig. 8d.

It should be noted that, depending on requirements for an application of interest, either of the pairs of ports (P1) and (P2) and (O1) and (O2) may be employed as input ports or output ports for the BAWR-SCF device 1, since the transmission of energy within the BAWR-SCF device 1 can be provided in either the direction from ports (P1) and (P2) to ports (O1) and (O2), or in the direction from ports (O1) and (O2) to ports (P1) and (P2). Being that energy may be transmitted within the BAWR-SCF device 1 in either direction, the device 1 functions similarly in each case and yields the same performance characteristics (described above) in each case.

In accordance with the preferred embodiment of the invention, the BAWR-SCF device 1 is constructed on a single wafer, and may be fabricated in accordance with the following steps to include layers listed in Tables 3, 4, and 5.

1. A first membrane layer is deposited on a substrate. The first membranae layer has a thickness of, by example, 62 nm, and is comprised of SiO_2.

2. A second membrane layer is deposited on the first membrane layer, and is patterned to produce a "cushion" layer for the remaining stack layers of the shunt BAW resonator 2 and the SCF 4 to be deposited in steps 3-8. Etching is then performed to remove portions of the deposited second membrane layer over which no further layers of the shunt BAW resonator 2 and the SCF 4 are to be deposited. The second membrane layer has a thickness of, by example, 213 nm, and is comprised of SiO_2.

3. An electrode layer is deposited over the layers formed in steps 1 and 2, and is then patterned to form a low r electrode layer of the BAW resonators 2 and 3 and the SCF 4. The lower electrode layer has a thickness of, for example, 250 nm, and is comprised of Mo.

4. A first piezoelectric layer is deposited on top of the lower electrode layer, and is patterned to form piezoelectric layers of the BAW resonators 2 and 3 and a lower piezoelectric layer of the SCF 4. These piezoelectric layers have thicknesses of, for example, 2362 nm, and are comprised of ZnO.

5. As a next step, another electrode layer is deposited over the lower layers of the devices 2, 3, and 4, and is th n patterned to form a middle electrode of the SCF 4. Portions of this deposited electrode layer that were deposited over the BAW resonators 2 and 3 are then removed by etching. The electrode layer has a thickness of, by example, 520 nm, and is comprised of Mo.

6. A next step includes depositing and patterning a second piezoelectric layer on the middle electrode of the SCF 4. The second piezoelectric layer has a thickness of, by example, 2363 nm, and is comprised of ZnO.

7. A next step includes depositing and patterning a further electrode layer over the lower layers of the BAW resonators 2 and 3 and the SCF 4, and thereby forming an upper layer of the devices 2, 3, and 4. The thickness of th upper electrode layer is, by example, 250 nm, and the electrode layer is comprised of Mo.

8. A further step includes depositing a protective layer, if needed, over the layers formed in the preceding steps.

It should be noted that, if the individual BAW resonators 2 and 3 and the SCF 4 include bridge structures, th n prior to the performance of step 1, steps are performed of forming etch openings (i.e., windows) through the membrane layers and the protective layer, and removing the sacrificial layer by wet etching.

Other topologies may also be provided for the BAWR-SCF device of the invention besides the one shown in Fig. 10a, depending on the particular frequency response characteristics required for a particular application of interest. By example, in cases in which it is required that narrower passband bandwidths be yielded (e.g., a 5 MHz passband bandwidth centered at 947.5 GHz instead of a 25 MHz passband bandwidth centered at 947.5 GHz), a BAWR-SCF circuit may be provided which is similar to that of Fig. 10a, except that the BAW resonators 2 and 3 forming the L segment 5 have an "inverted" configuration. Referring to Fig. 10d, for example, a BAWR-SCF circuit 16 is provided which is similar to the BAWR-SCF circuit 1 of Fig. 10a, except that the BAW resonators 2 and 3 of BAWR-SCF circuit

provide greater stopband attenuation than is provided by the BAWR-SCF circuit 1. The BAWR-SCF circuit 13 also provides better stopband attenuation characteristics than are provided by, for example, th prior art BAW ladder filter 44 of Fig. 8f. By example, and referring to both the frequency response of Fig. 11b and the frequency response of the BAW ladder filter 44 shown in Fig. 8g, the level of stopband attenuation provided by the BAW filter 13 is improved by over 20 dB over that of BAWR-SCF circuit 44, while the passband bandwidths and passband ripple magnitudes of the respective frequency responses ar similar.

In cases in which it is necessary to provide a BAWR-SCF circuit that yields similar frequency respons characteristics as the BAWR-SCF circuit 13 of Fig. 11a, but which yields a narrower passband bandwidth than is yielded by the BAWR-SCF circuit 13, a BAWR-SCF circuit 13' in accordance with the invention may be provided, as is shown in Fig. 11c. The BAWR-SCF circuit 13' includes BAW resonators 2, 3, 14 and 15, and a SCF 4. In a preferred embodiment of the invention, upper electrode 26 of BAW resonator 3 is coupled to node (I1), and a lower electrode 24 of the BAW resonator 3 is coupled to a node (I2). BAW resonator 2 is connected between node (I2) and ground node (G1). Upper electrode 26 of BAW resonator 2 is coupled to ground node (G1) and lower electrode 24 of the BAW resonator 2 is coupled to the node (I2). Lower electrode 24 of the SCF 4 is coupled to node (I2), middle electrode 26' of the SCF 4 is coupled to ground node (G2), and upper electrode 25 of the SCF 4 is coupled to a node (I3) of the BAWR-SCF circuit 13'. Lower electrode 24 of the BAW resonator 15 is coupled to node (I3) and upper electrode 26 of the BAW resonator 15 is coupled to ground node (G3). Lower electrode 24 of BAW resonator 14 is coupled to node (I3) and upper electrode 26 of the BAW resonator 14 is coupled to node (O).

Owing to the configuration of the BAWR-SCF circuit 13', the BAWR-SCF circuit 13' yields a passband bandwidth that is more narrow than the passband bandwidth yielded by the BAWR-SCF circuit 13 of Fig. 11a. As can be appreciated, the inclusion of the BAW resonators 14 and 15 in the BAWR-SCF circuit 13' enables the circuit 13' to provide better stopband attenuation characteristics than can be provided by, for example, the BAWR-SCF circuit 16, which does not include BAW resonators 14 and 15. Also, in an ideal case, the BAW resonators 14 and 15 influence the passband bandwidth of the BAWR-SCF 13', narrowing it to a certain extent.

Referring to Fig. 12, a balanced filter (also referred to as a "BAWR-SCF circuit") 17 in accordance with the invention will now be described. In accordance with a preferred embodiment of the invention, the balanced filter 17 comprises BAW resonators 2, 3, 3', 14, 14' and 15, a SCF 4, and a SCF 4'. BAW resonator 2 and a BAW resonator 3 are connected in an "L segment" configuration similar to that described above. More particularly, BAW resonator 2 is connected across nodes (I1) and (I2) of the filter 17. Upper electrode 26 of the BAW resonator 2 is connected to node (I1) and lower electrode 24 of the BAW resonator 2 is connected to node (I2). Upper electrode 26 of BAW resonator 3 is also connected to node (I1), and lower electrode 24 of the BAW resonator 3 is coupled to lower electrode 24 of the SCF 4. Middle electrode 26' of the SCF 4 is coupled to ground node (G), and upper electrode 25 of the SCF 4 is connected to lower electrode 24 of BAW resonator 14. Upper electrode 26 of the BAW resonator 14 is connected to node (O1).

Also in the preferred embodiment of the invention, upper electrode 26 of BAW resonator 3' is connected to node (I2), and lower electrode 24 of the BAW resonator 3' is connected to lower electrode 24 of SCF 4'. Middle electrode 26' of the SCF 4' is coupled to ground node (G), and upper electrode 25 of the SCF 4' is coupled to lower electrode 24 of resonator 14'. Upper electrode 26 of BAW resonator 14' is coupled to node (O2). BAW resonator 15 is connected across nodes (O1) and (O2). Lower electrode 24 of the BAW resonator 15 is coupled to node (O1), and upper electrode 26 of BAW resonator 15 is coupled to node (O2). As can be appreciated, with this configuration, vias V1, V2, V3, and V4 are provided in the structure of the BAWR-SCF circuit 17. The BAWR-SCF circuit 17 functions in a similar manner as the BAWR-SCF circuit 13, and exhibits a similar passband response as that (shown in Fig. 11b) exhibited by the BAWR-SCF circuit 13. However, in the balanced filter 17 of Fig. 12, there is a 180 degree phase differential between signals that are applied to one of the pairs of nodes (I1) and (I2) and (O1) and (O2), and between output signals at the other pair of these nodes, although these signals have equal magnitudes.

The balanced filter 17 may be employed in cases in which, by example, it is required to filter a balanced signal traveling between two circuit components (e.g., amplifiers) having balanced inputs and outputs. The use of the balanced filter 17 in this case is more advantageous than the use of a non-balanced filter since, if a non-balanced filter w r employed between the circuit components, the balanced signal output by a first one of the components would need to be converted to an un-balanced signal before being applied to the non-balanced filter, and would then need to b converted back to a balanced signal after being output by the non-balanced filter.

As can be appreciated in view of the above description, each of the BAWR-SCF circuits described above yields frequency response characteristics that are improved over those exhibited individual BAW ladder filters and individual SCF devices. Because the BAWR-SCF circuits do not require the use of tuning elements (e.g., inductors) to enable the devices to yield the improved frequency response characteristics, whereas individual BAW ladder filters and individual SCF devices do require the use of tuning elements to yield somewhat improved frequency responses, the BAWR-SCF devices of the invention can be smaller in size and less complex than the individual BAW ladder filters and individual SCF devices which incorporate tuning elements.

Each of the various embodiments described above can be operated over frequencies ranging from approximately

4. Middle electrode 26' of SCF 4 is coupled to ground node (G5). BAW resonator 14 of the second portion (RX1) is preferably connected within the device so that lower electrode 24 of the BAW resonator 14 is coupled to the lower electrode 24 of the SCF 4, and so that upper electrode 26 of the BAW resonator 14 is coupled to a node (I4). BAW resonator 15 is preferably connected within the second portion (RX1) of the duplexer 51 so that upper electrode 26 of the resonator 15 is coupled to node (I4) and lower electrode 24 is coupled to node (G6). With this configuration, th second portion (RX1) of the duplexer 51 includes vias V3 and V4.

It should be noted that the BAWR-SCF circuits 53 and 55 of the respective first and second portions (TX1) and (RX1) of duplexer 51 may have other topologies than those shown in Fig. 13. For example, the BAWR-SCF circuits 53 and 55 of the respective first and second portions (TX1) and (RX1) may have topologies that are similar to those shown in blocks 156 and 164 of Figs. 17b and 18b, respectively. As can be appreciated, the topologies in this cas are the same as the topologies of respective portions (TX1) and (RX1) of Fig. 13, except that a lesser number of BAW resonators are employed. An input 152 and output 154 are also shown in Fig. 17b, and an input 160 and an output 162 are also shown in Fig. 18b. Also by example, the respective first and second portions (TX1) and (RX1) of duplexer 51 may have topologies that are similar to any of the devices shown in the above-described Figs. 10d and 11c, or any other suitable topology may be employed, depending on applicable performance criteria for the duplexer 51.

In accordance with the invention, the duplexer 51 is constructed so that the first portion (TX1) yields a passband (e.g., a transmit band) over selected frequencies that are different than selected passband (e.g., receive band) frequencies of the second portion (RX1). That is, the series BAW resonators of the first portion (TX1) preferably are tuned to yield a parallel resonance that enables the first portion (TX1) to provide a notch at a selected frequency f_2 abov the passband of the first portion (TX1), and the parallel BAW resonators of the first portion (TX1) are preferably tuned to yield a series resonance that enables the first portion (TX1) to provide a notch at a selected frequency f_1 below the passband of first portion (TX1). The series BAW resonators of the second portion (RX1) of duplexer 51 preferably are tuned to yield a parallel resonance that enables the second portion (RX1) to provide a notch at a selected frequency f_4 above the passband of the second portion (RX1), and the parallel BAW resonators of the second portion (RX1) are preferably tuned to yield a series resonance that enables the second portion (RX1) to provide a notch at a selected frequency f_3 below the passband of the second portion (RX1). Also, the series and parallel BAW resonators of the portions (RX1) and (TX1) of the duplexer 51 are preferably constructed so as to yield series and parallel resonances, respectively, at or near the desired center frequencies of the respective portions (RX1) and (TX1) of the duplexer 51, and the SCFs of these portions (RX1) and (TX1) of the duplexer 51 are also preferably constructed so as to yield series resonances at the respective, desired center frequencies of these portions (RX1) and (TX1) of the duplexers.

Preferably, the passbands of the respective first and second portions (TX1) and (RX1) of the duplexer 51 are sufficiently spaced apart from one another on the frequency spectrum so as to enable a high level of selectivity to b provided for the respective portions (RX1) and (TX1) of the duplexer 51.

Fig. 15 illustrates the frequency responses of the first portion (TX1) and the second portion (RX1) of the duplexer 51 for an exemplary case in which the duplexer 51 is designed for use in a GSM transceiver (i.e., in GSM applications, the transmit band ideally extends between the frequencies of 890 MHz to 915 MHz, and the receive band ideally extends between the frequencies of 935 Mhz to 960 Mhz). For this application, the BAW resonators and the SCF of the respective portions (TX1) and (RX1) of the duplexer 51 are assumed to include the layers and layer dimensions shown in Tables 6 and 7, respectively, below. Also, the BAW resonators and the SCF of the respective portions (TX1) and (RX1) are assumed to include "bridge" structures (i.e., the devices include membrane layers), and the antenna port is assumed to have a resistance of 50 Ohms.

TABLE 7: Dimensions of TX1 Portion

Series BAW Resonators 3 and 14		Shunt BAW Resonators 2 and 15		SCF 4		BAW Resonator RS1	
Layer	Thickness	Layer	Thickness	Layer	Thickness	Layer	Thickness
				upper electrode	254nm		
				upper piezolayer	3060nm		
upper electrode	254nm	upper electrode	254nm	ground electrode	254nm	upper electrode	254nm
lower piezoelectric layer	2483nm	piezoelectric layer	2483nm	lower piezoelectric layer	2483nm	piezoelectric layer	2483nm
electrode	254nm	lower electrode	254nm	lower electrode	254nm	lower electrode	254nm
1. membrane layer	50nm	1. membrane layer	50nm	1. membrane layer	50nm	1. membrane layer	50nm
2. membrane layer	--	2. membrane layer	255nm	2. membrane layer	255nm	2. membrane layer	--
area of electrode	248um· 248um	area of electrode	342um· 342um	area of electrode	373um· 373um	area of electrode	268um· 268um

The frequency response (for the transmit band) of the first portion (TX1) is labeled "57" in Fig. 15, and the frequency response (for the receive band) of the second portion (RX1) is labeled "59" in Fig. 15. As can be appreciated in view

Preferably, the dual duplexer device 71 comprises at least one antenna (ANT), amplifiers (AMP1), (AMP2), (AMP3), and (AMP4), and first and second duplexer portions 81 and 82, respectively. The first duplexer portion 81 includes a filter block (TX1'), and a filter block (TX2'), and the second duplexer portion 82 includes a filter block (RX1') and a filter block (RX2'). In a preferred embodiment of the invention, each of the filter blocks (TX1') and (TX2') preferably includes similar components as the first, transmit portion (TX1) of the duplexer 51 described abov . For example, Fig. 17a shows a filter block 150 that includes a BAWR-SCF circuit similar to the transmit portion (TX1) of the duplexer 51. In the preferred embodiment of the invention, the filter block 150 forms the filter blocks (TX1') and (TX2') of Fig. 16, input 152 of Fig. 17a forms respective inputs 72' and 73 of Fig. 16, and output 154 of Fig. 17a forms respective outputs 74 and 75 of Fig. 16.

Also in the preferred embodiment of the invention, each of the filter blocks (RX1') and (RX2') of the dual duplexer 71 includes similar components as the second, receive portion (RX1) of the duplexer 51 described above. By example, Fig. 18a shows a filter block 158 that includes a BAWR-SCF circuit similar to the receive portion (RX1) of the duplexer 51. In the preferred embodiment of the invention, the filter block 158 forms the filter blocks (RX1') and (RX2') of Fig. 16, input 160 forms respective inputs 77 and 78 of Fig. 16, and output 162 forms respective outputs 79 and 79' of Fig. 16.

Inputs 72' and 73 of the respective filter blocks (TX1') and (TX2') are coupled to outputs of the respective amplifiers (AMP1) and (AMP2). Outputs 74 and 75 of the respective filter blocks (TX1') and (TX2') of the dual duplexer 71 are coupled to an antenna port (A1') via a common node 76'. Inputs 77 and 78 of the respective filter blocks (RX1') and (RX2') are coupled to antenna port (A1') via a common node 76", and respective outputs 79 and 79' of the respectiv filter blocks (RX1') and (RX2') are coupled to amplifiers (AMP3) and (AMP4), respectively. The amplifiers (AMP1) and (AMP2) are preferably connected at their inputs to some further circuitry such as, by example, transmitter circuitry (TX) of a dual-mode transceiver device. Also, the amplifiers (AMP3) and (AMP4) are preferably connected at their outputs to some further circuitry such as, by example, receiver circuitry (RX) of the dual-mode transceiver device.

As described above, the dual duplexer 71 can be employed to provide filtering in a dual-mode transceiver device. As such, and according to a presently preferred embodiment of the invention, the BAW resonators and SCFs of each portion (TX1'), (TX2'), (RX1'), and (RX2') of the dual duplexer 71 are constructed in a manner so that the filter block (TX1') yields a passband (e.g., a transmit band) over a first selected band of frequencies, the filter block (TX2') yields a passband (e.g., a transmit band) over a second selected band of frequencies, the filter block (RX1') yields a passband (e.g., a receive band) over a third selected band of frequencies, and the filter block (RX2') yields a passband (e.g., a receive band) over a fourth selected band of frequencies. In this manner, during times when the dual duplexer 71 is connected within the dual-mode transceiver device, the filter block (TX1') filters signals that are output by transmitter (TX) of the transceiver device and which have a frequency within the passband of the filter block (TX1'), before the signals are transmitted from the transceiver device over antenna (ANT). The filter block (TX2') filters signals that are output by the transmitter (TX) of the transceiver device and which have a frequency within the passband of the filt r block (TX2'), before the signals are transmitted from the transceiver device over the antenna (ANT). Also within the transceiver device, the filter block (RX1') of the dual duplexer 71 filters signals that are received by the antenna (ANT) and which have a frequency within the passband of the block (RX1'), and then provides filtered signals to the receiver circuitry (RX) of the transceiver device. Similarly, the filter block (RX2') of the dual duplexer 71 filters signals that are received by the antenna (ANT) and which have a frequency within the passband of the block (RX2'), and then provides filtered signals to the receiver circuitry (RX) of the transceiver device.

Preferably, the passbands of the respective filter blocks (TX1'), (TX2'), (RX1'), and (RX2') of the dual duplexer 71 are sufficiently spaced apart from one another on the frequency spectrum so as to enable a high level of selectivity to be provided for the blocks (RX1'), (RX2'), (TX1'), and (TX2') of the dual duplexer 71. Also, as for the duplexer 51 described above, for cases in which the passbands of the respective blocks (TX1'), (TX2'), (RX1'), and (RX2') ar sufficiently spaced apart from one another on the frequency spectrum, the resonators RS1 and RS2 need not be employed. Moreover, appropriate FET switches may be employed within the dual duplexer 71, if desired.

It should be noted that, depending on, e.g., applicable performance criteria, the filter blocks (TX1'), (TX2'), (RX1'), and (RX2') may include BAWR-SCF circuits having other topologies than those shown in Figs. 17a and 18a. For example, the filter blocks (TX1') and (TX2') may have topologies that are similar to those shown in block 156 of Fig. 17b, and the filter blocks (RX1') and (RX2') may have topologies that are similar to those shown in block 164 of Fig. 18b. As can be appreciated, the topologies in this case are the same as the topologies of the BAWR-SCF circuits of Figs. 17a and 18a, respectively, except that a lesser number of BAW resonators are employed. In this embodiment, input 152 and output 154 of Fig. 17b form the inputs 72' and 73 and the outputs 74 and 75, respectively, of filter blocks (TX1') and (TX2'). Also, input 160 and output 162 of Fig. 18b form inputs 77 and 78 and outputs 79 and 79', respectively, of filter blocks (RX1') and (RX2'). It should also be noted that the BAWR-SCF circuits of the respective filter blocks (TX1'), (TX2'), (RX1'), and (RX2') of dual duplexer 71 may have topologies that are similar to any of the devices shown in the above-described Figs. 10d and 11c, or any other suitable topology may be employed, depending on applicable performance criteria for the duplexer 51.

While the invention has been particularly shown and described with respect to preferred embodiments thereof, it

said third BAW resonator, said fourth BAW resonator also having a second terminal coupled to said second lead between said node and said second one of said second pair of ports.

6. A BAW filter according to any of the preceding claims, wherein said passband response yielded by said BAW filter has upper and lower edges that are more steeply-sloped than respective upper and lower edges of a passband response that can be provided by a single SCF device.

7. A BAW filter according to any of claims 1 to 5, wherein said BAW filter provides a higher level of stopband attenuation than can be provided by a BAW ladder filter that includes no SCF devices and no tuning elements.

8. A BAW filter according to any of claims 1 to 3, wherein said first BAW resonator is tuned to yield a resonance at a first resonant frequency and said second BAW resonator is tuned to yield a resonance at a second resonant frequency, wherein said lower notch is a function of said second resonant frequency, wherein said upper notch is a function of said first resonant frequency, and wherein said center frequency f_c is a function of another resonant frequency yielded by at least one of said first and second BAW resonators and a resonant frequency yielded by said first SCF.

9. A BAW filter as set forth in claim 8, wherein said first SCF is tuned to yield a second harmonic resonance at a frequency which is approximately equal to said center frequency f_c.

10. A BAW filter as set forth in claim 9, wherein each of said first BAW resonator and said second BAW resonator includes a piezoelectric layer having a thickness of T, wherein said first SCF includes a pair of piezoelectric layers each having a respective thickness of T, and wherein said frequency of said second harmonic resonance of said first SCF is a function of said respective thickness of each one of said pair of piezoelectric layers of said first SCF.

11. A BAW filter according to any of claims 1 to 5, wherein at least one of said first BAW resonator, said second BAW resonator, and said first SCF includes one of a membrane structure and an acoustic mirror structure.

12. A Bulk Acoustic Wave (BAW) filter, comprising:

a first pair of ports;

a second pair of ports;

a first lead connected between a first and a second one of said first pair of ports;

a second lead connected between a first and a second one of said second pair of ports;

a first plurality of BAW resonators, said first plurality of BAW resonators including a first BAW resonator connected in series in said first lead, said first plurality of BAW resonators also including a second BAW resonator connected between said first lead and said second lead; and

a first Stacked Crystal Filter (SCF), said first SCF having first and second terminals connected in said first lead between said first BAW resonator and one of said first pair of ports, said first SCF also having a third terminal connected to a node in said second lead;

a second plurality of BAW resonators, said second plurality of BAW resonators including a third and a fourth BAW resonator, said third BAW resonator connected in series in said first lead between said first SCF and said second one of said first pair of ports, said fourth BAW resonator having a first terminal coupled to said first lead between said third BAW resonator and said second one of said first pair of ports, said fourth BAW resonator also having a second terminal coupled to said second lead between said node and said second one of said second pair of ports.

a fifth BAW resonator connected in series in said second lead, said fifth BAW resonator having a first terminal coupled to said first one of said second pair of ports;

a sixth BAW resonator connected in series in said second lead, said sixth BAW resonator having a first terminal coupled to said second one of said second pair of ports; and

18. A duplex filter according claim 16 or claim 17 , wherein said input of at least one of said first and second portions includes a respective first pair of ports, wherein said output of said at least one of said portions includes a respectiv second pair of ports, wherein said BAWR-SCF circuit of said at least one of said portions further comprises:

a first lead connected between a first one of said first pair of ports and a first one of said second pair of ports; and

a second lead connected between a second one of said first pair of ports and a second one of said second pair of ports;

wherein said plurality of BAW resonators of said BAWR-SCF circuit of said at least one of the portions includes a first BAW resonator connected in series in said first lead and a second BAW resonator connected between said first lead and said second lead, wherein said SCF of said BAWR-SCF circuit of said at least one of th portions has first, second, and third terminals, said first and second terminals being connected in said first lead between said first BAW resonator and said first one of said second pair of ports, said third terminal b ing connected to said second lead.

19. A duplex filter as set forth in claim 18, wherein said BAWR-SCF circuit of said at least one of said portions further comprises:

a third BAW resonator interposed between said SCF and said first one of said second pair of ports; and

a fourth BAW resonator having a first terminal coupled between said third BAW resonator and said first one of said second pair of ports, said fourth BAW resonator also having a second terminal coupled to said second lead.

20. In a dual-mode transceiving device having a transmitter portion, a receiver portion, and at least one antenna, a double duplex filter, said double duplex filter comprising:

a first duplexer, said first duplexer including a first filter and a second filter, each of said first and second filters having a respective first pair of ports coupled to an output of said transmitter portion, each of said first and second filters also having a respective second pair of ports, at least a first one of said second pair of ports of each of said first and second filters being coupled to said at least one antenna, each of said first and second filters comprising a respective Bulk Acoustic Wave (BAW) filter circuit, said first and second filters being tun d to yield passbands over a first frequency band and a second frequency band, respectively; and

a second duplexer, said second duplexer including a third filter and a fourth filter, each of said third and fourth filters having a respective first pair of ports, at least a first one of said first pair of ports of each of said third and fourth filters being coupled to said at least one antenna, each of said third and fourth filters also having a respective second pair of ports coupled to an input of said receiver portion, each of said third and fourth filters comprising a respective BAW filter circuit, said third and fourth filters being tuned to yield passbands over a third frequency band and a fourth frequency band, respectively; and wherein said BAW filter circuit of each of said first, second, third, and fourth filters includes:

a first lead connected between the first one of the first pair of ports of the filter and a first one of the second pair of ports of said filter;

a second lead connected between a second one of the first pair of ports of the filter and a second one of the second pair of ports of said filter;

a first BAW resonator connected in series in said first lead;

a second BAW resonator connected between said first lead and said second lead; and

a Stacked Crystal Filter (SCF) having first and second terminals connected in said first lead between said first BAW resonator and the first one of said second pair of ports of the filter, said SCF also having a third terminal connected to a node of said second lead.

21. In a dual-mode transceiving device as set forth in claim 20, wherein the BAW filter circuit of each of said first,

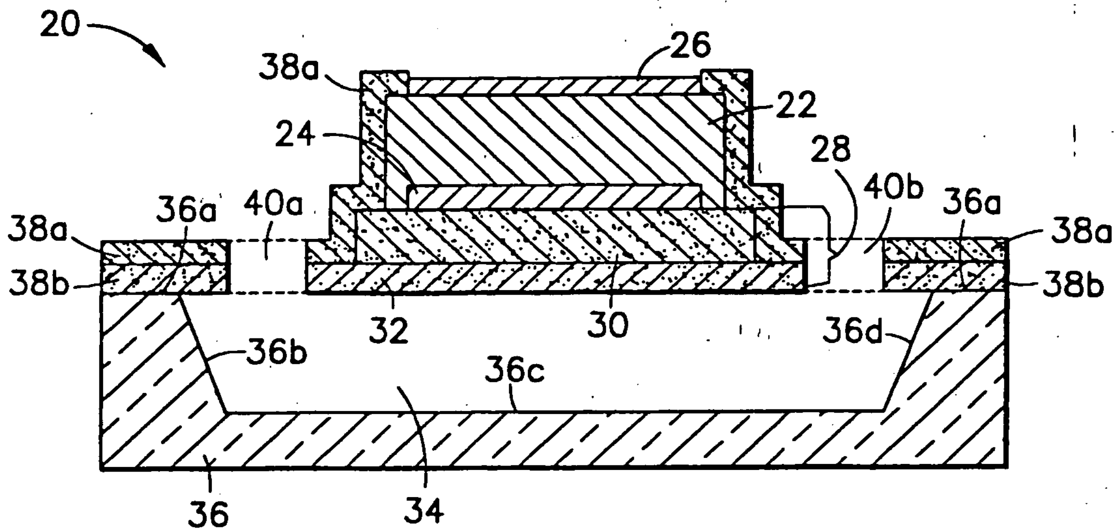

20
26
38a
22
24
28
40b
36a
40a
36a
38a
38a
38b
38b
32
30
36d
36b
36c
36
34

FIG. 1a

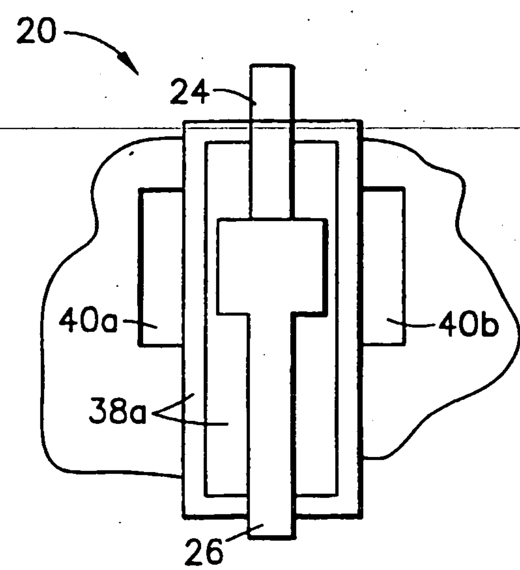

20
24
40a
40b
38a
26

FIG. 1b

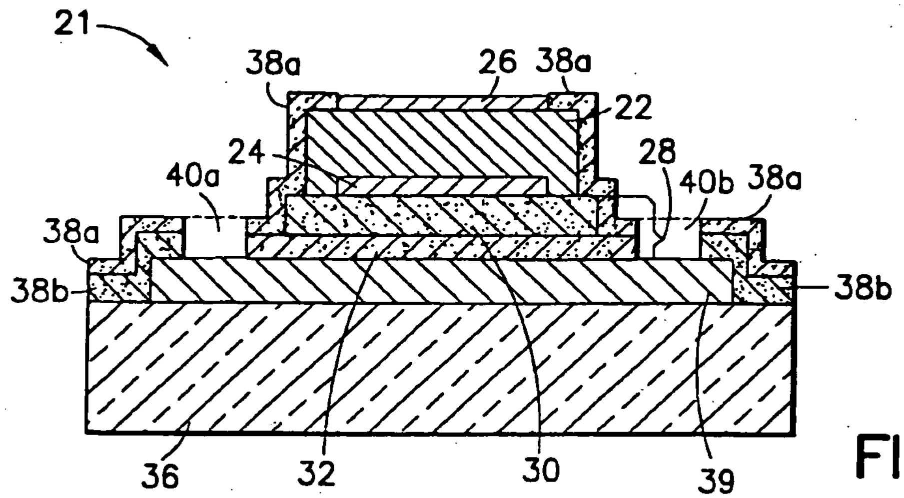


FIG. 2

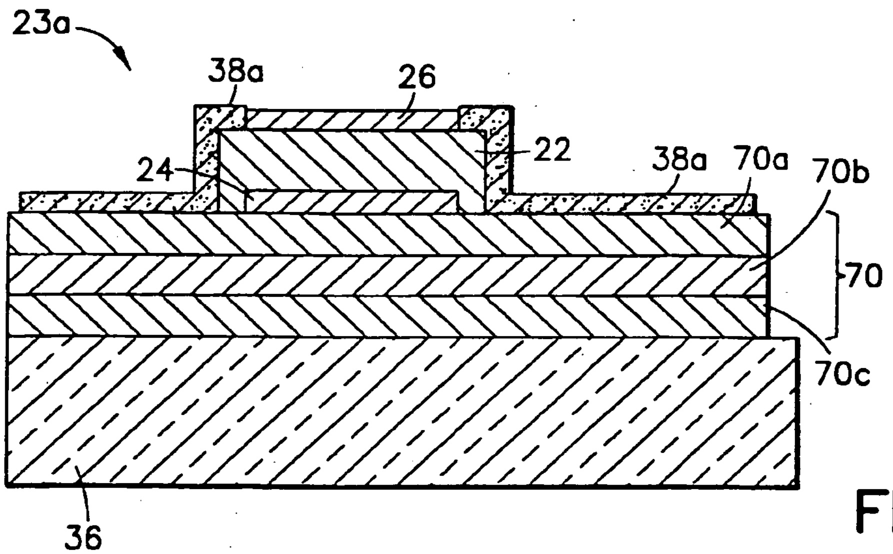


FIG. 3a

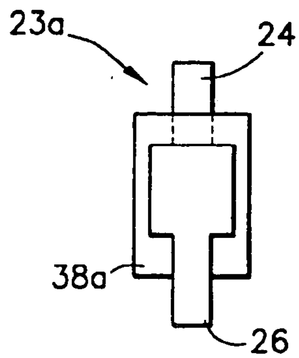


FIG. 3b

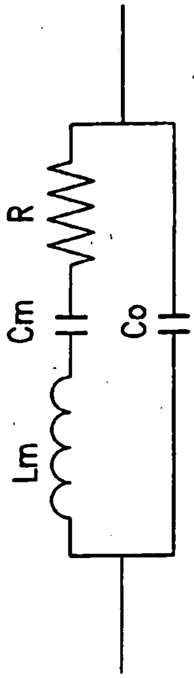


FIG. 4b

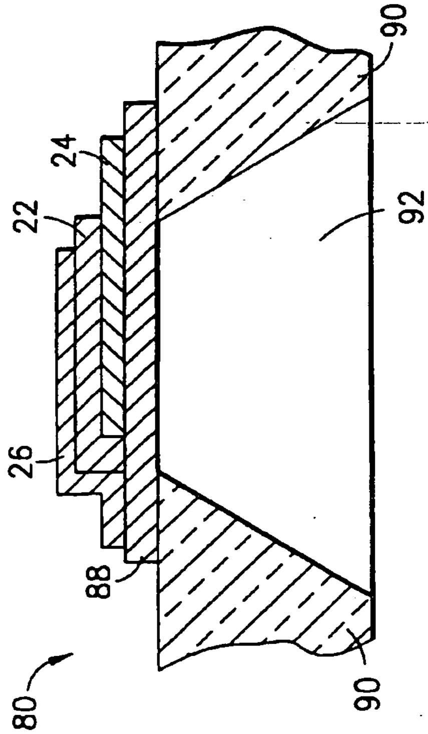


FIG. 4a

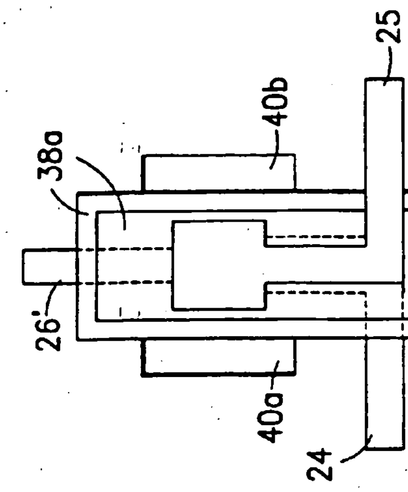


FIG. 5b

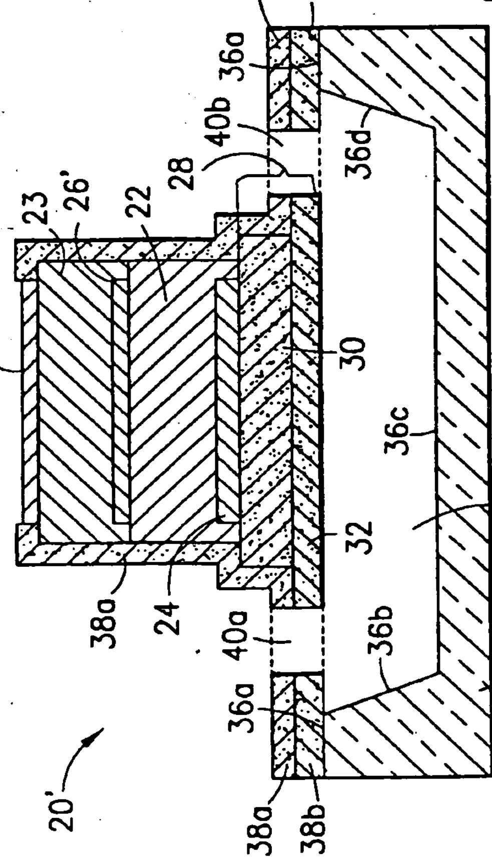


FIG. 5a

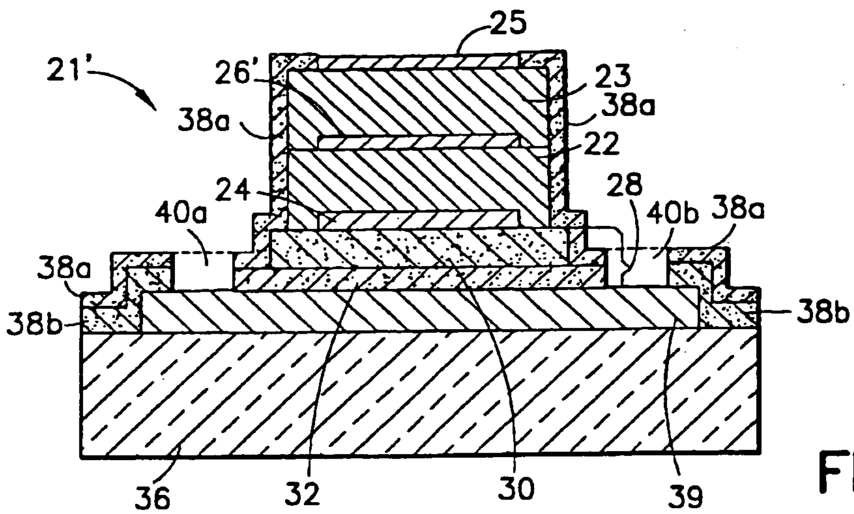


FIG. 6

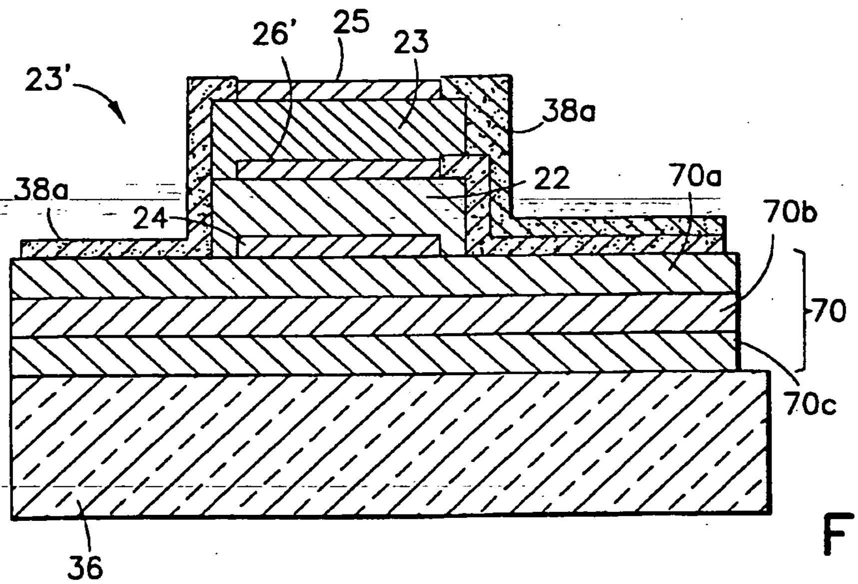


FIG. 7a

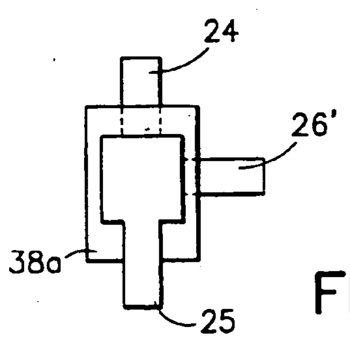


FIG. 7b

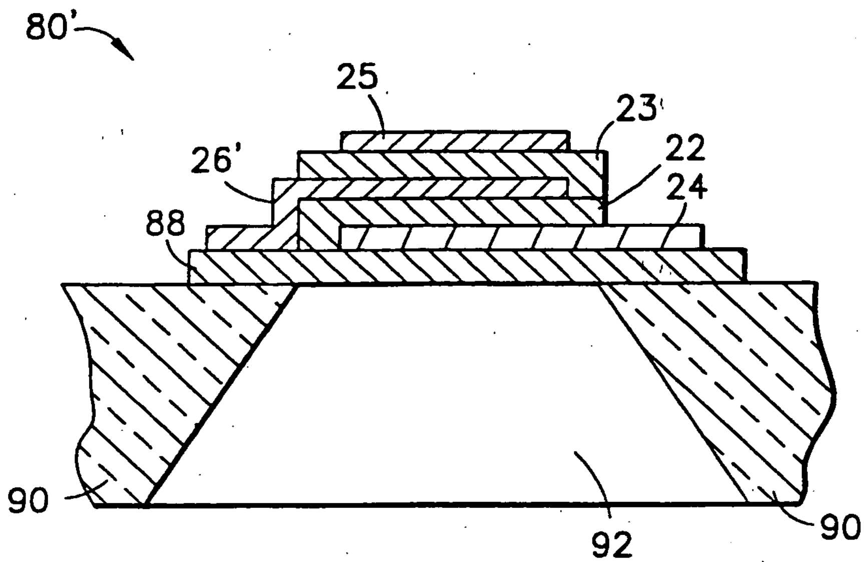


FIG. 8a

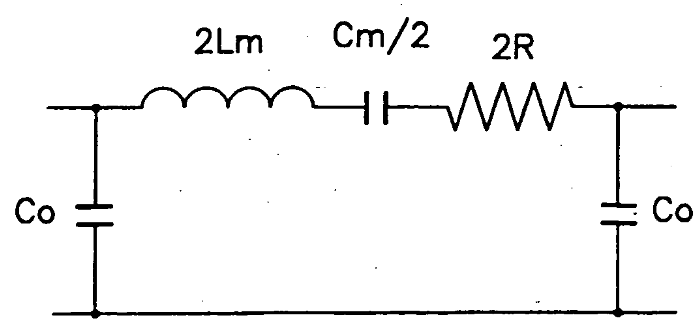


FIG. 8b

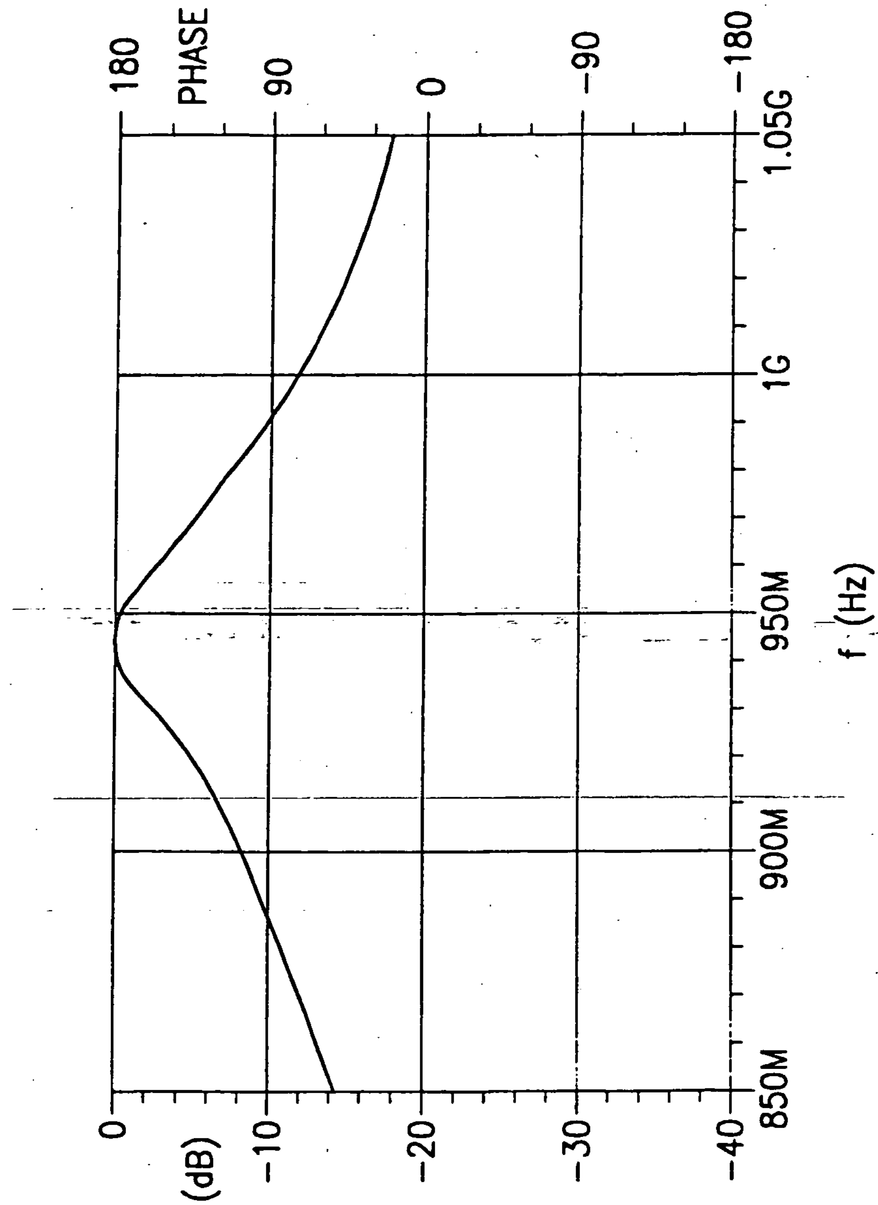


FIG.8c
PRIOR ART

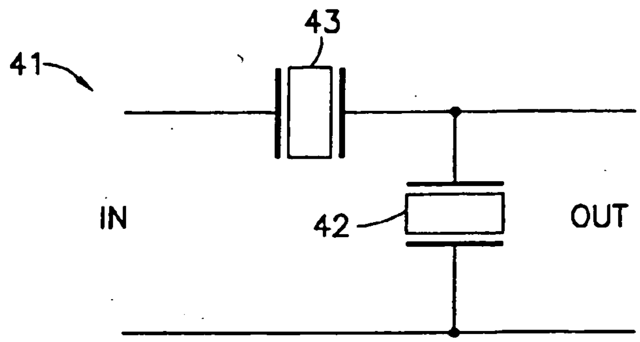


FIG.8d
PRIOR ART

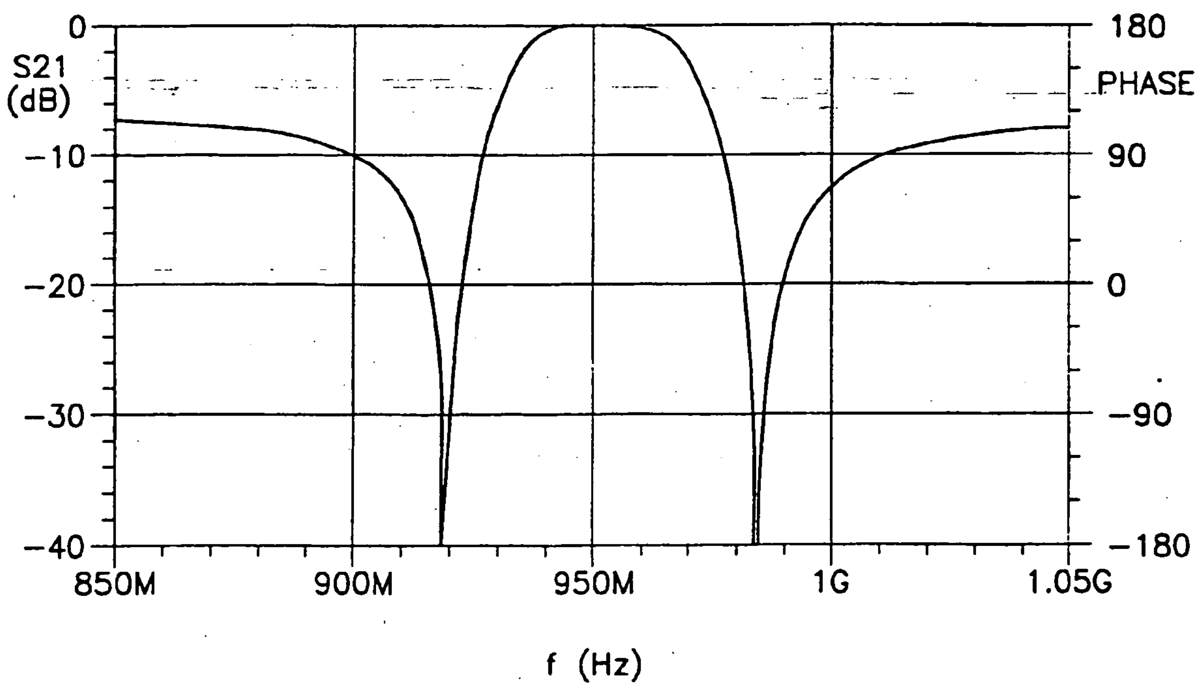


FIG.8e
PRIOR ART

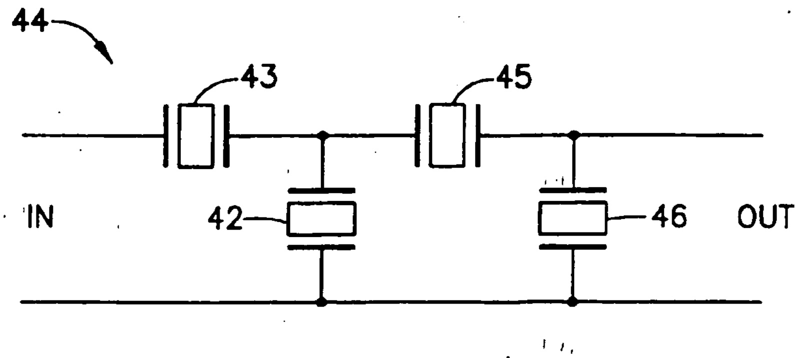


FIG. 8f
PRIOR ART

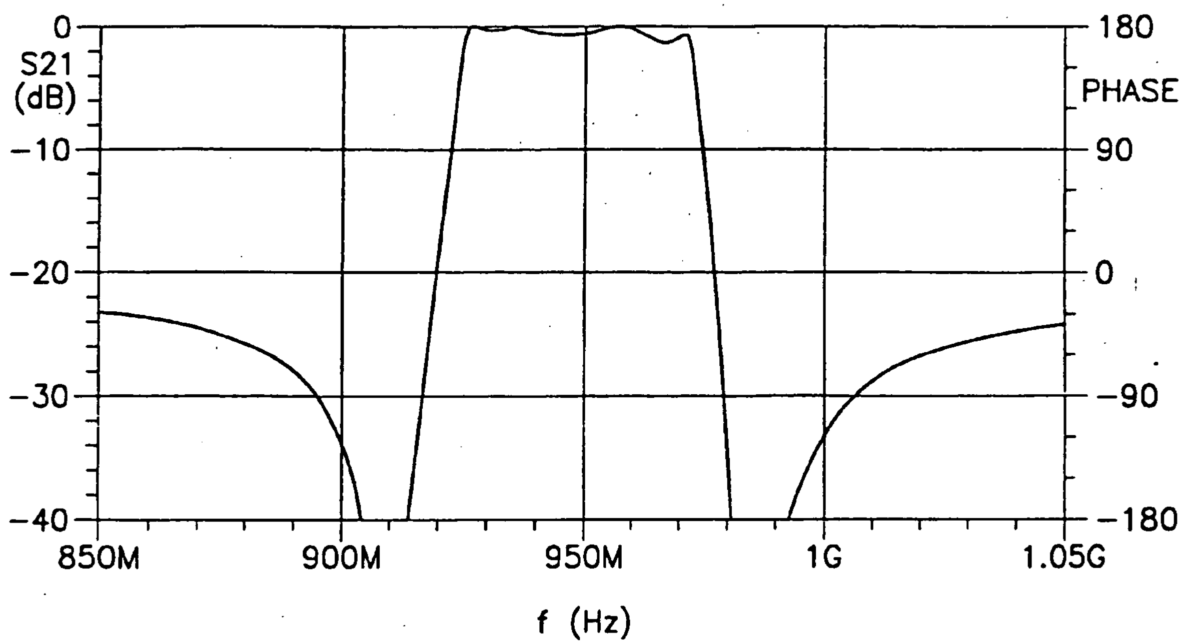


FIG. 8g
PRIOR ART

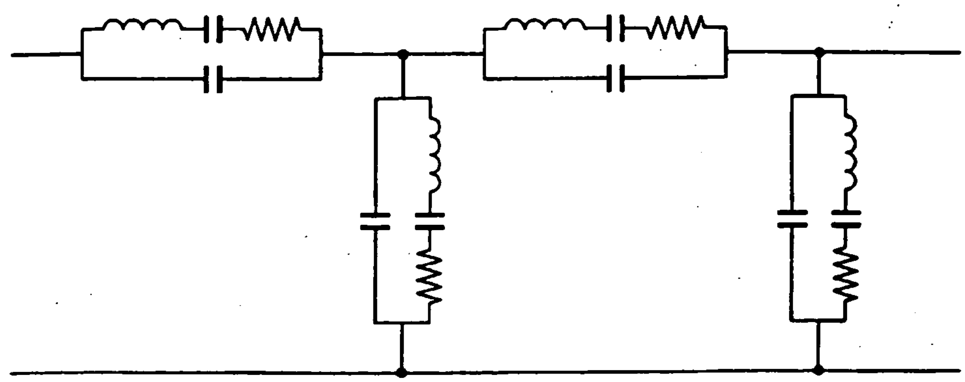


FIG. 8h
PRIOR ART

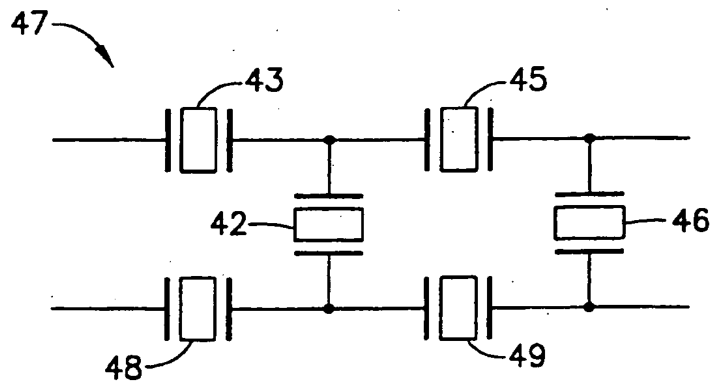


FIG. 8i
PRIOR ART

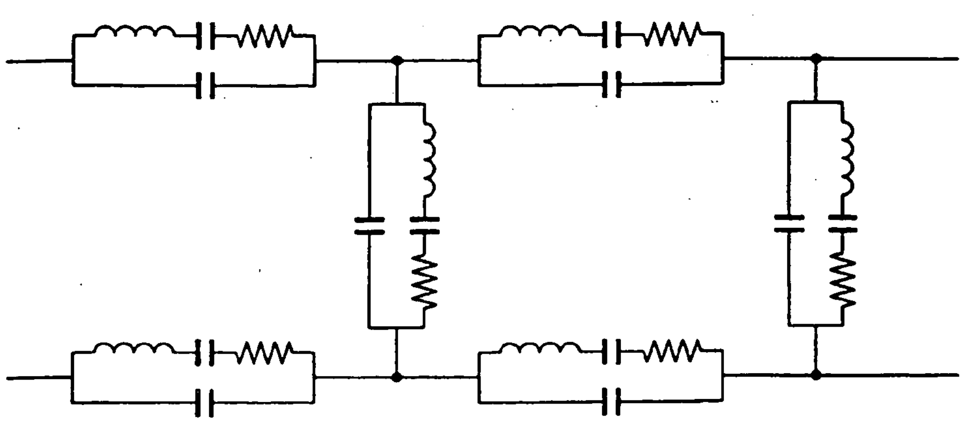


FIG. 8j
PRIOR ART

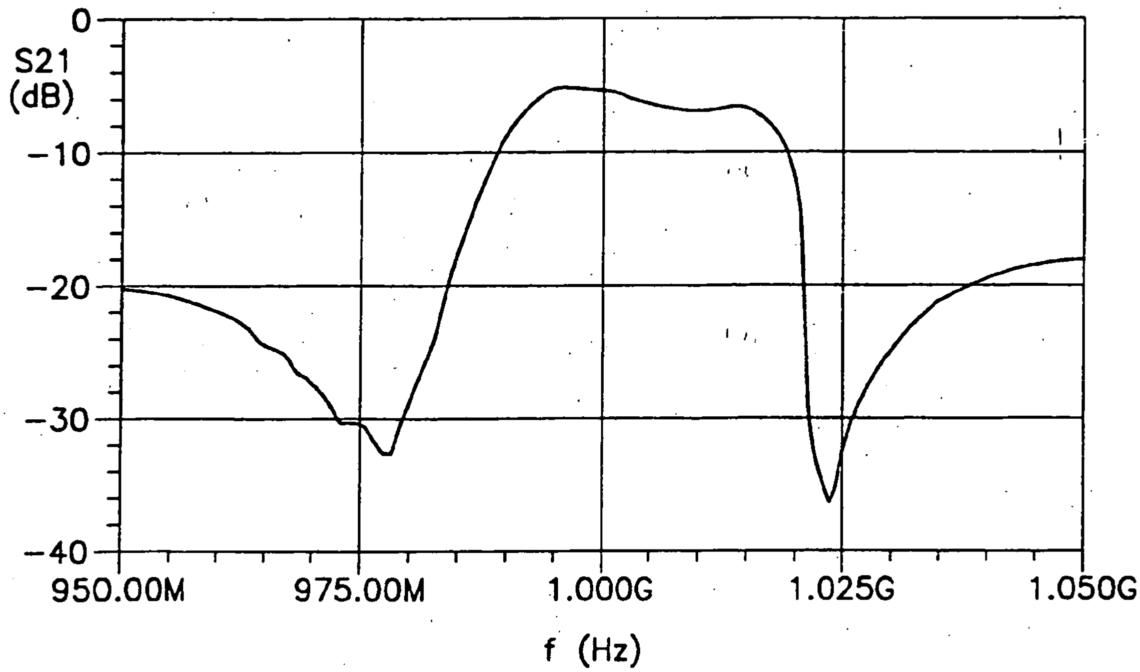


FIG.9a
PRIOR ART

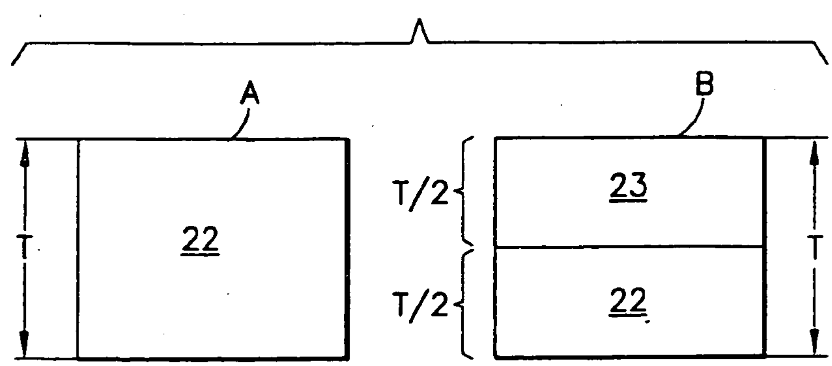


FIG.9b

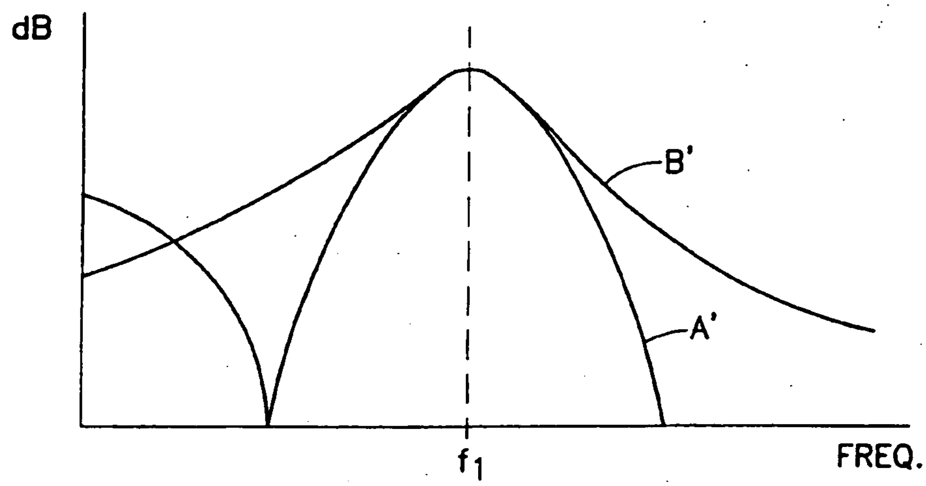


FIG.9c

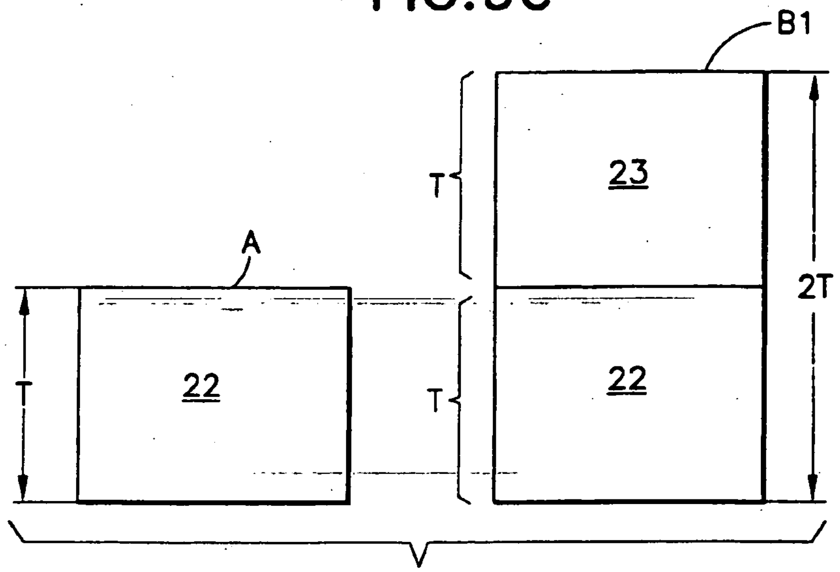


FIG.9d

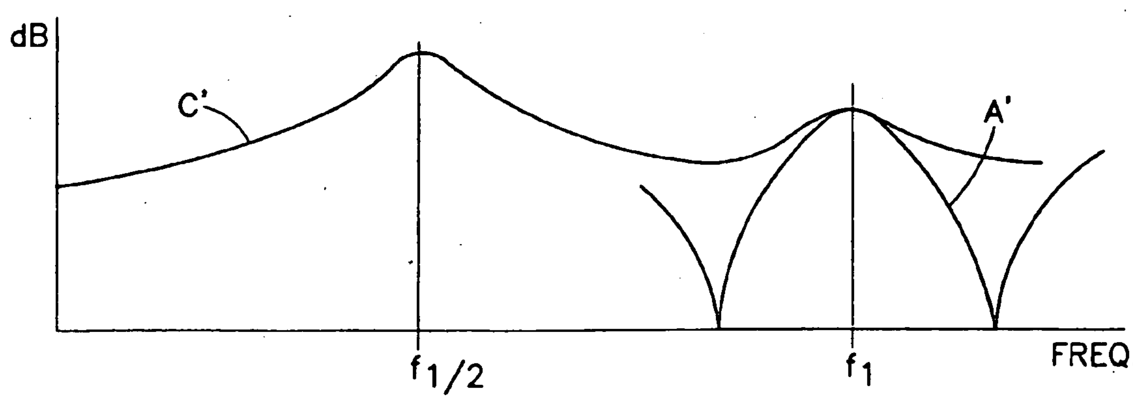


FIG.9e

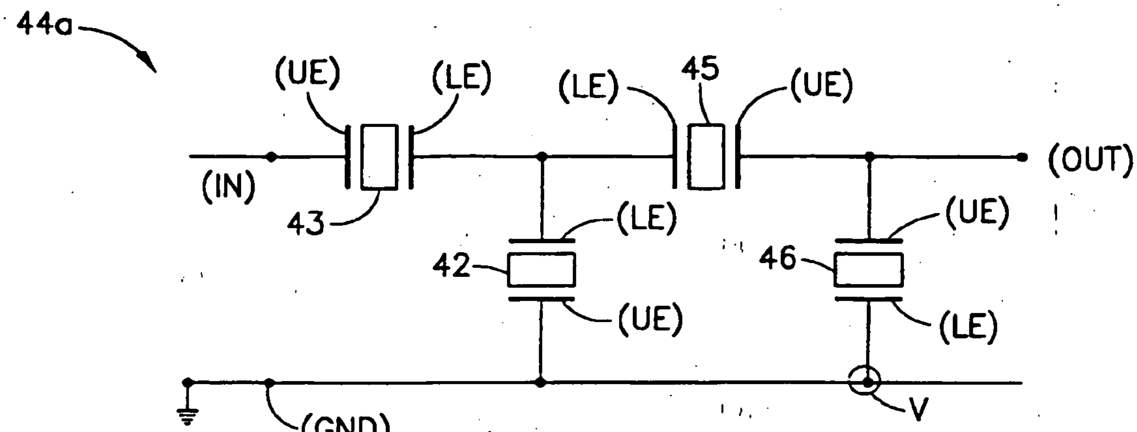


FIG.9f

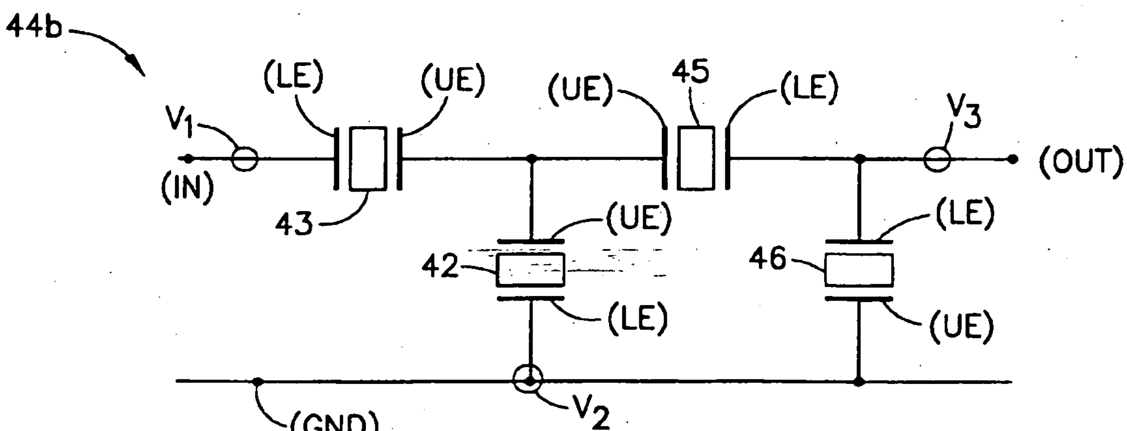


FIG.9g

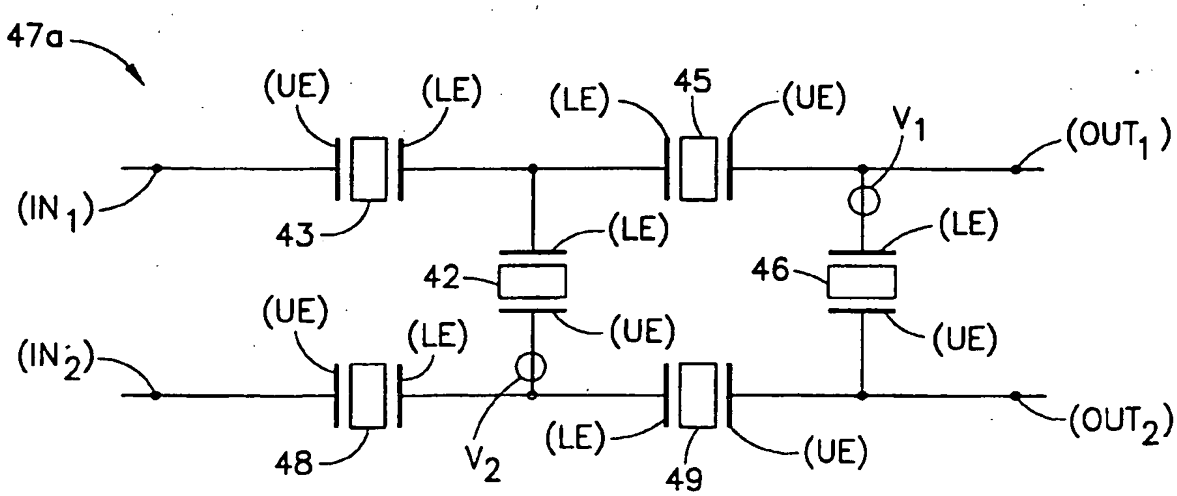


FIG.9h

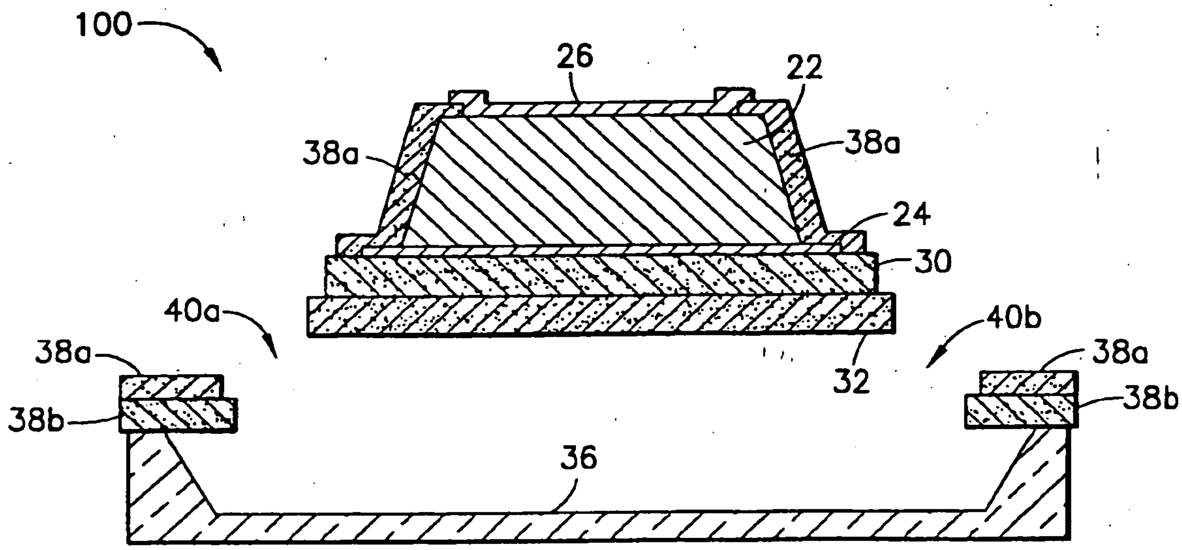

100
26
22
38a
38a
24
30
40a
40b
38a
38a
32
38b
38b
36

FIG.9i

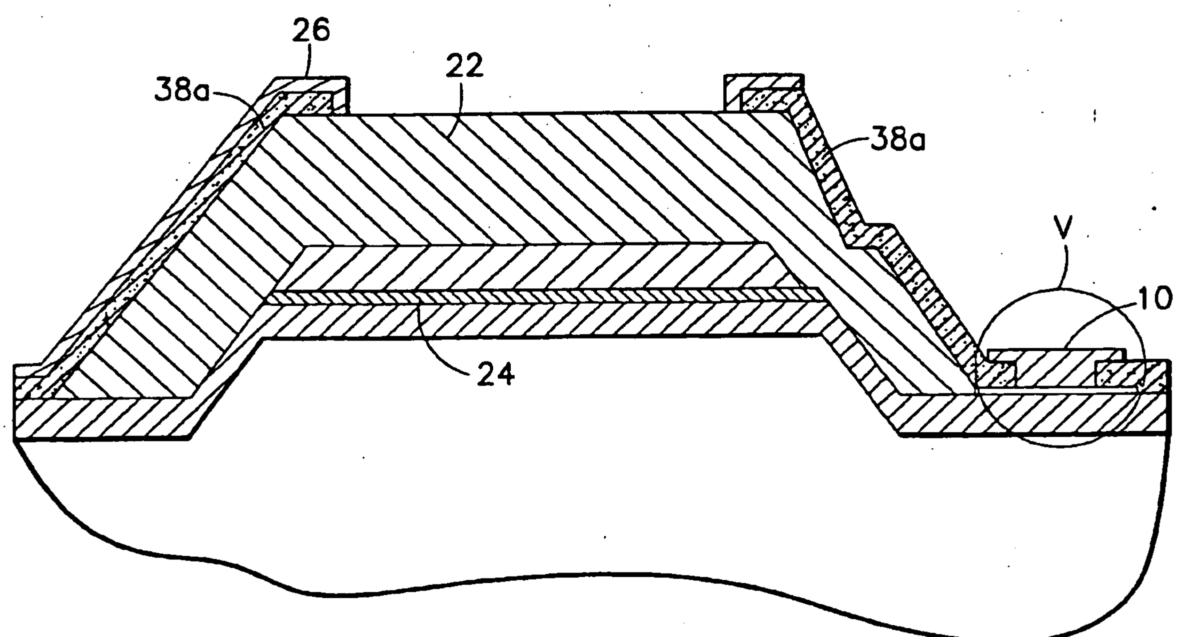

26
22
38a
38a
V
101
24

FIG.9j

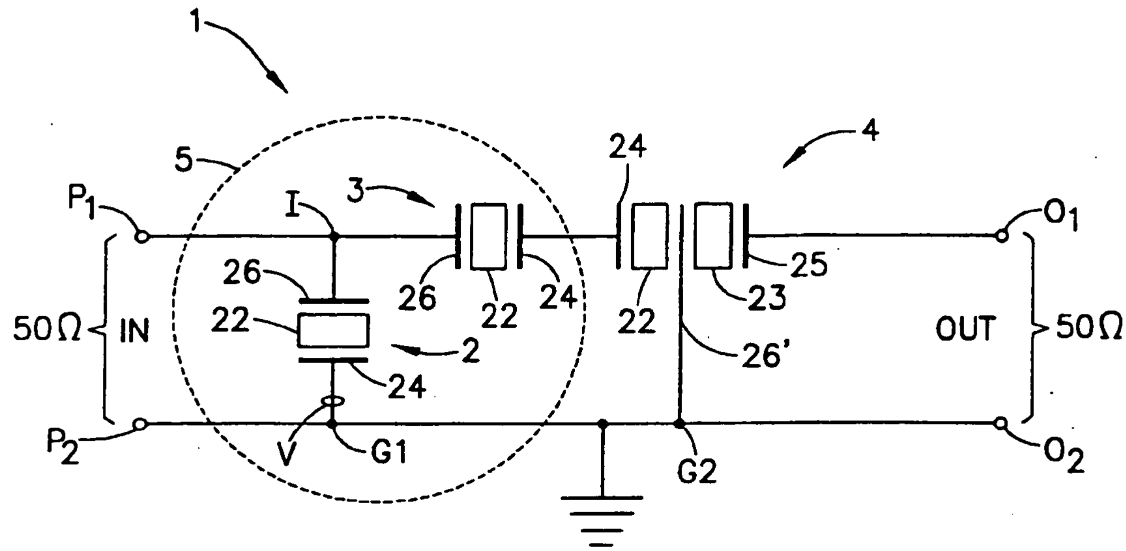


FIG.10a

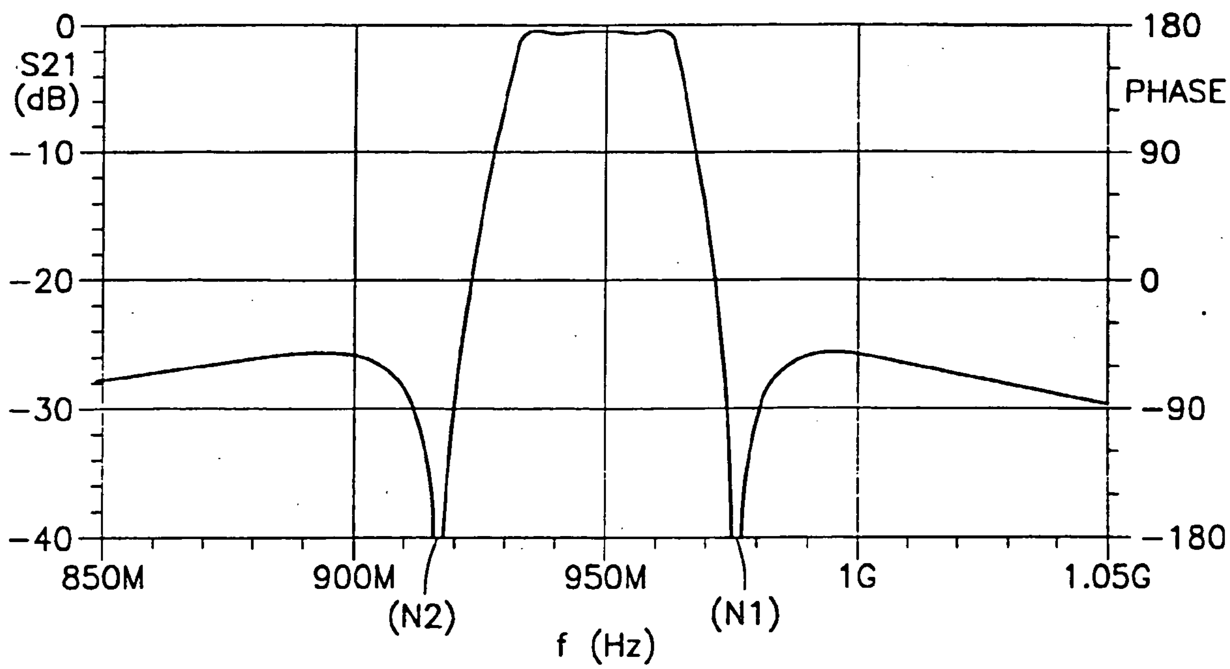


FIG.10b

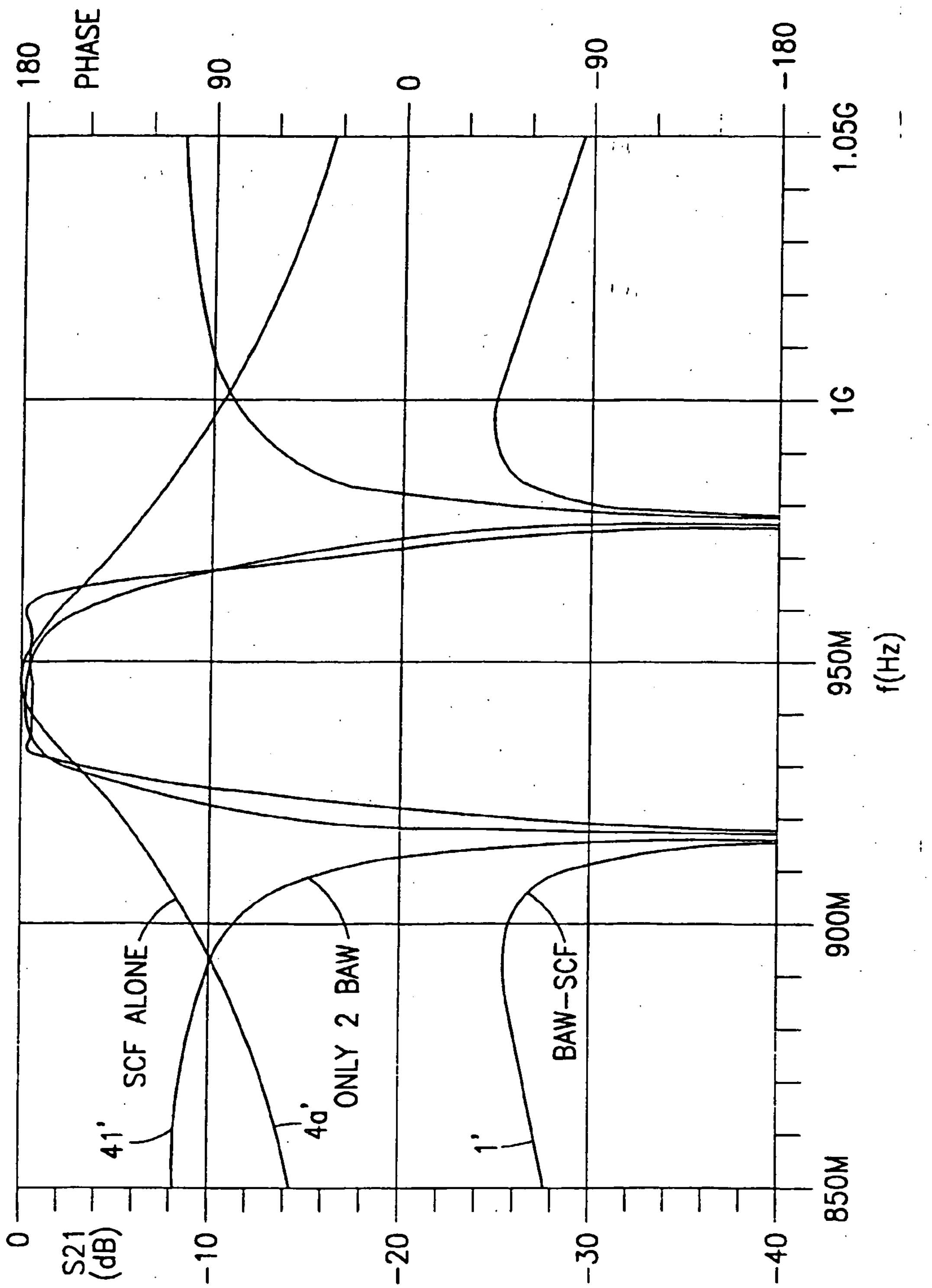

S21
(dB)
0
-10
-20
-30
-40
PHASE
180
90
0
-90
-180
850M
900M
950M
1G
1.05G
f(Hz)
SCF ALONE
ONLY 2 BAW
BAW-SCF
41'
4a'
1'

FIG.10c

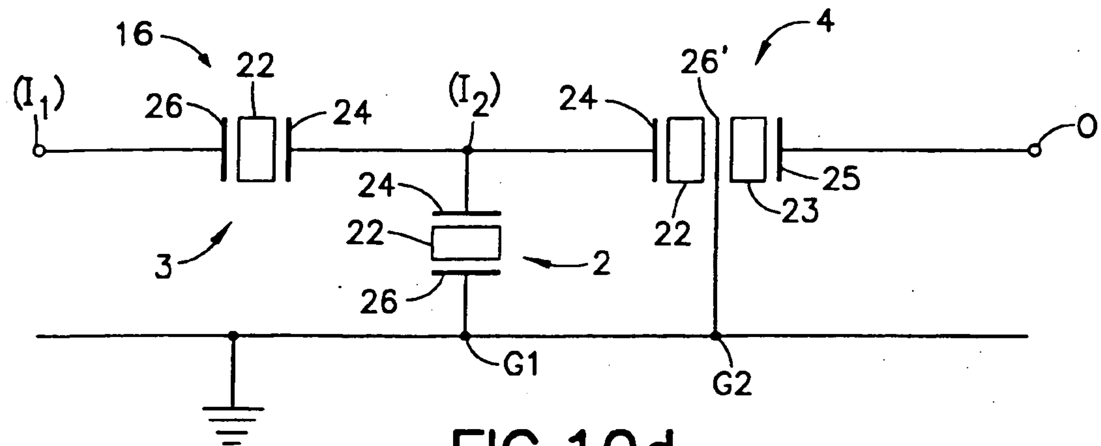


FIG.10d

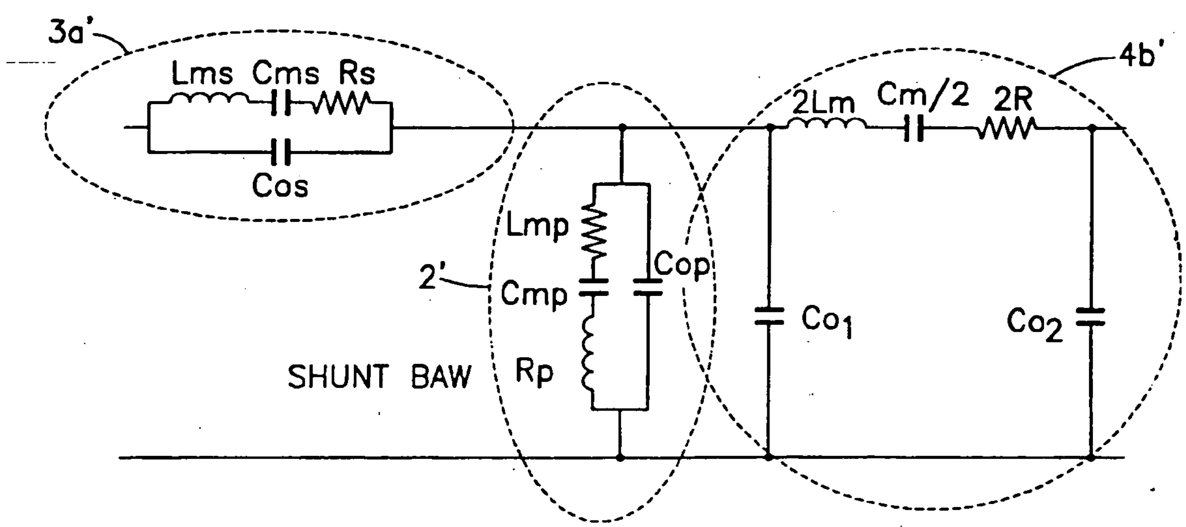


FIG.10e

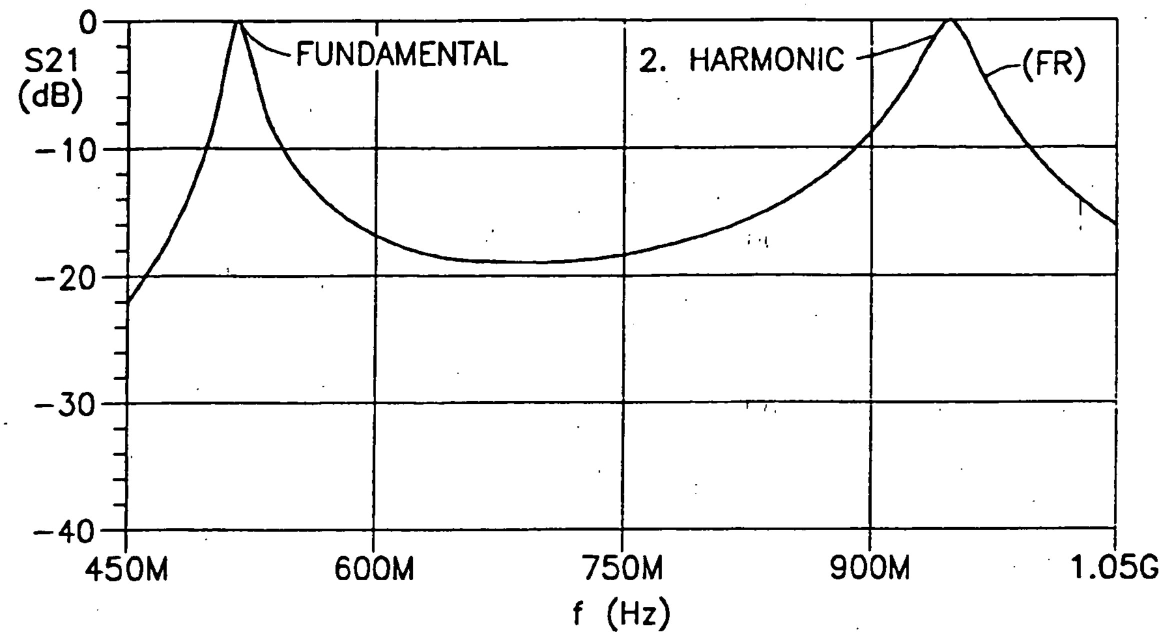


FIG.10f

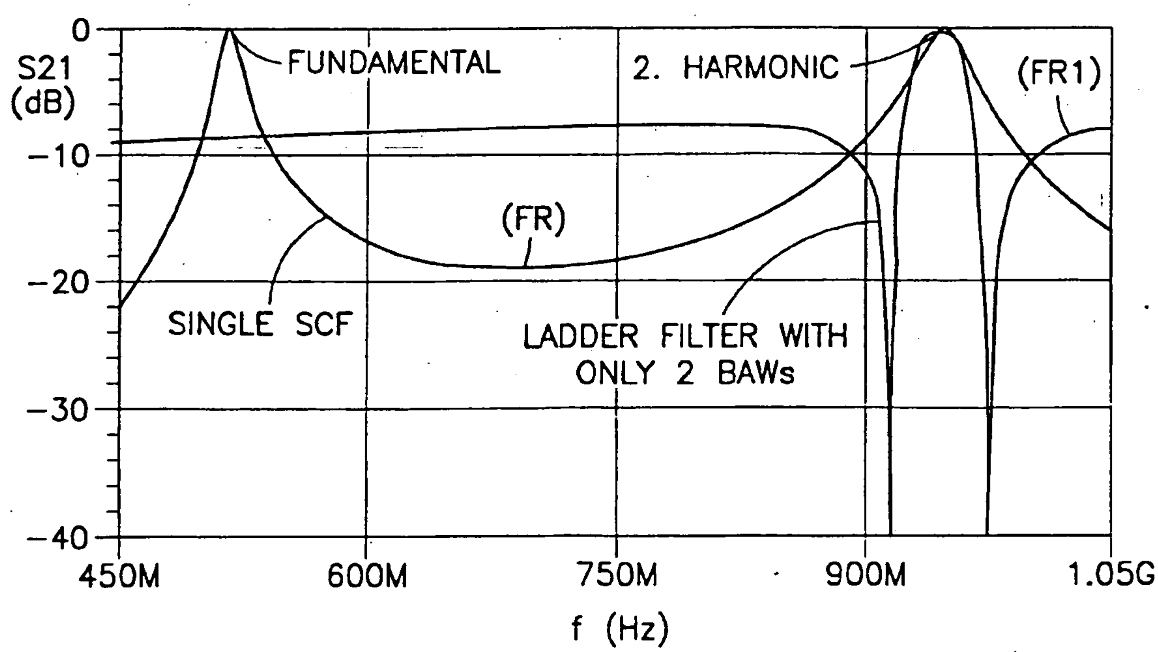
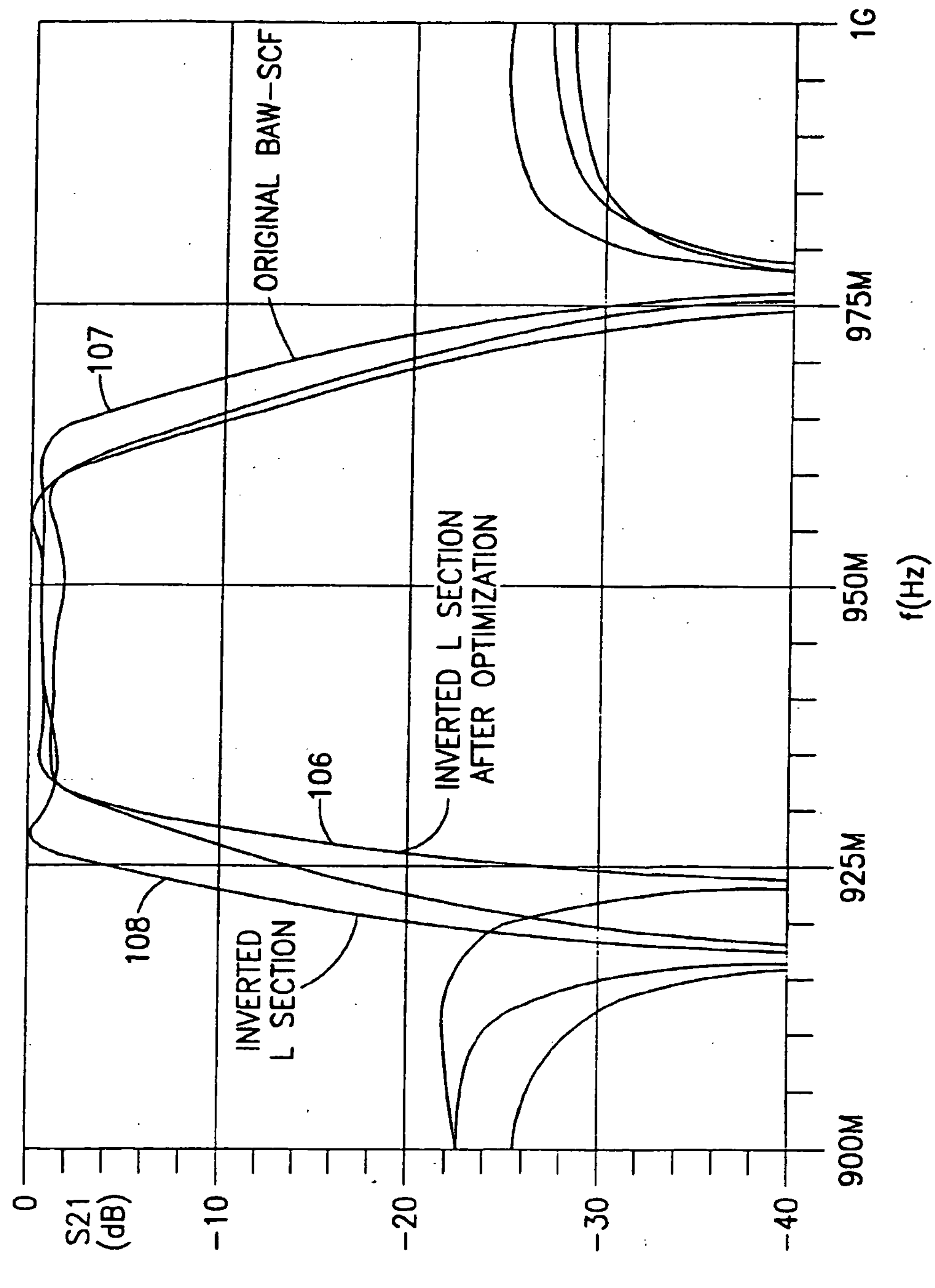


FIG.10g



ORIGINAL BAW-SCF
107
106
108
INVERTED L SECTION AFTER OPTIMIZATION
INVERTED L SECTION
S21 (dB)
0
-10
-20
-30
-40
900M
925M
950M
975M
1G
f(Hz)

FIG. 10h

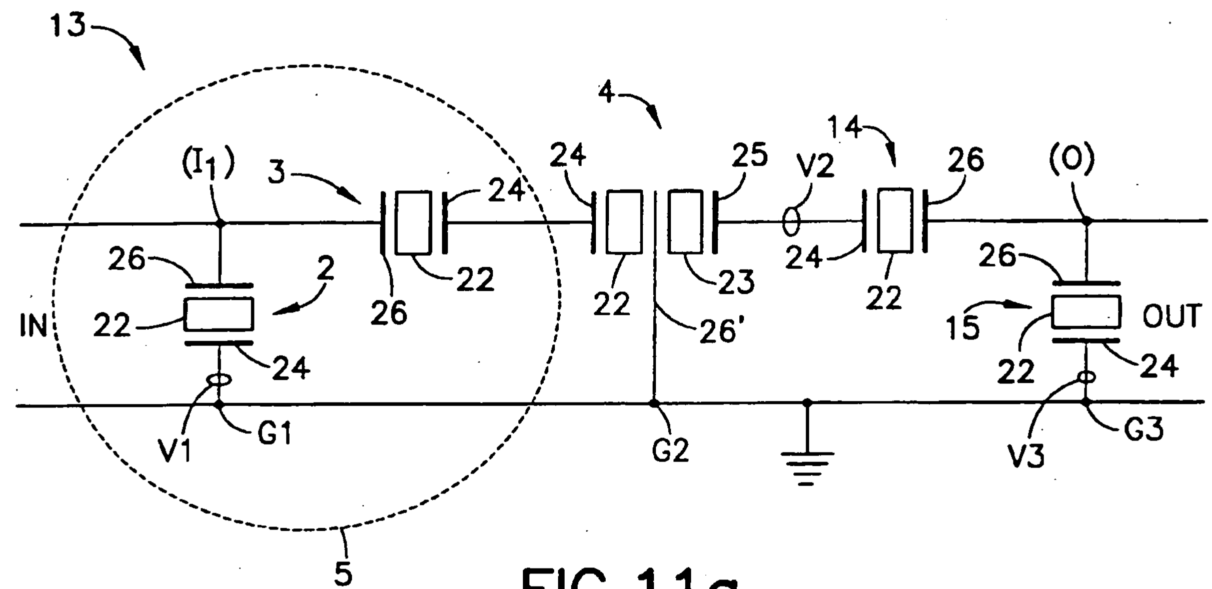


FIG.11a

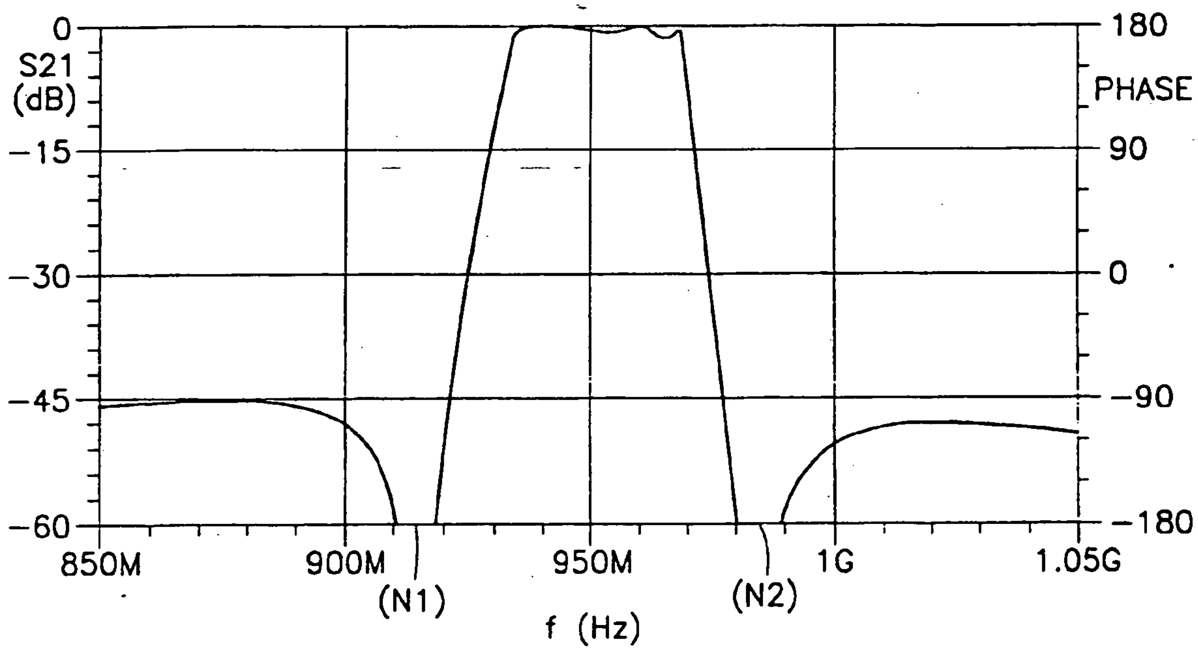


FIG.11b

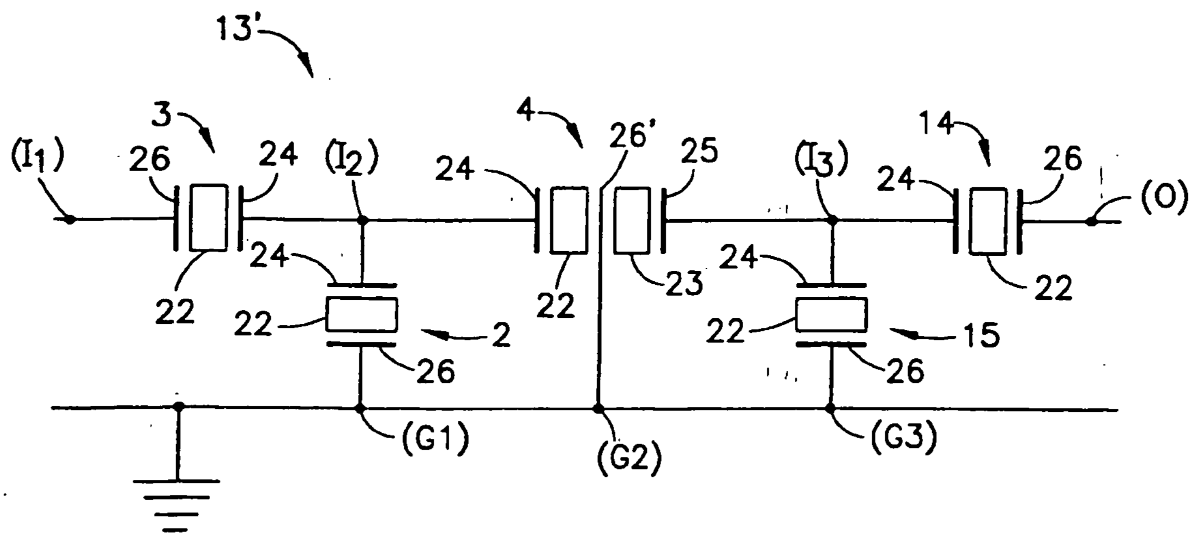


FIG.11c

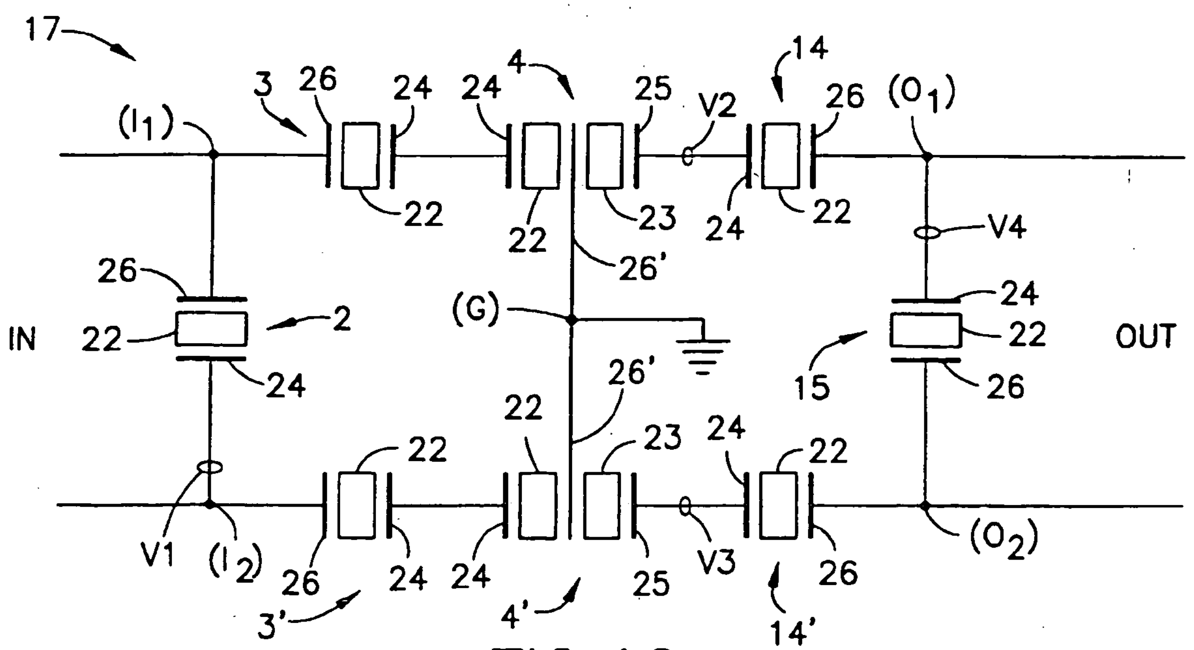


FIG.12

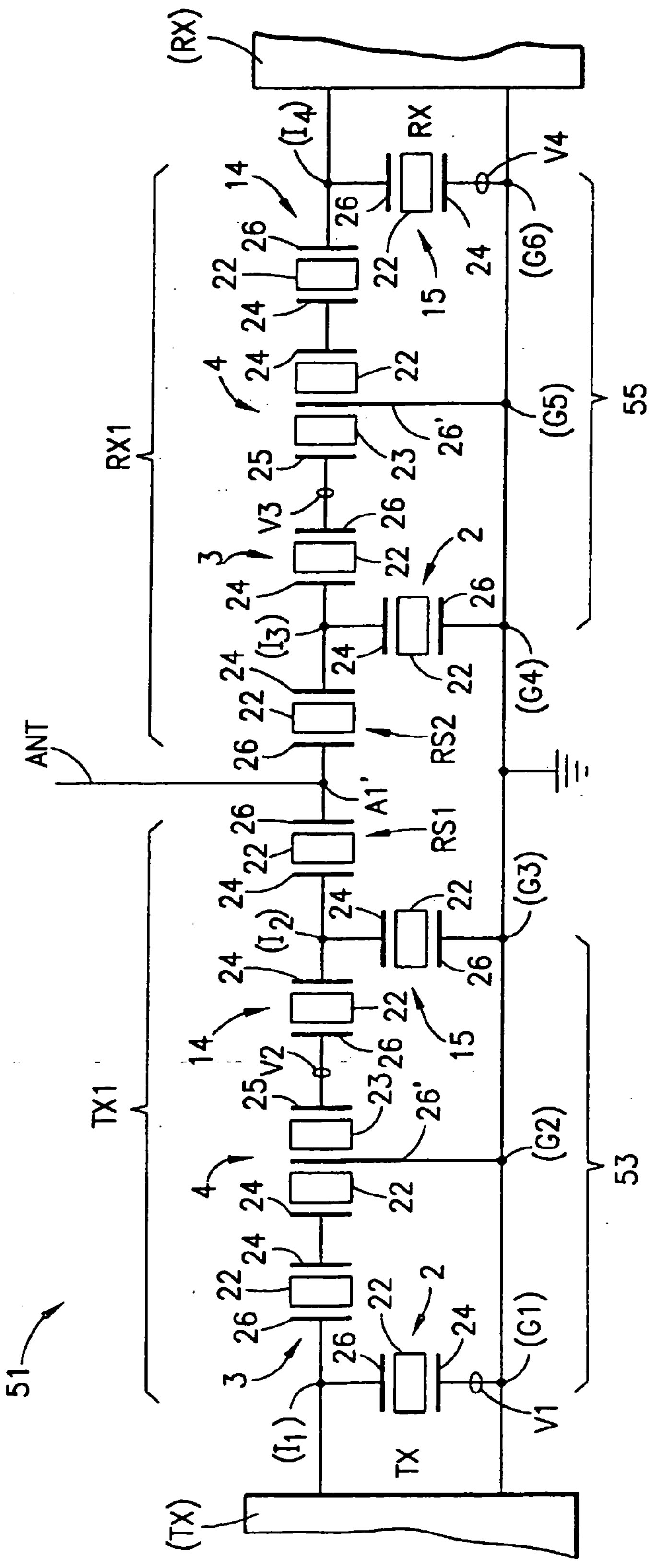

(RX)
RX
(TX)
TX
ANT
RX1
TX1
51
53
55
RS1
RS2
A1'
V1
V2
V3
V4
(G1)
(G2)
(G3)
(G4)
(G5)
(G6)
(I_1)
(I_2)
(I_3)
(I_4)
2
3
4
14
15
22
23
24
25
26
26'

FIG.13

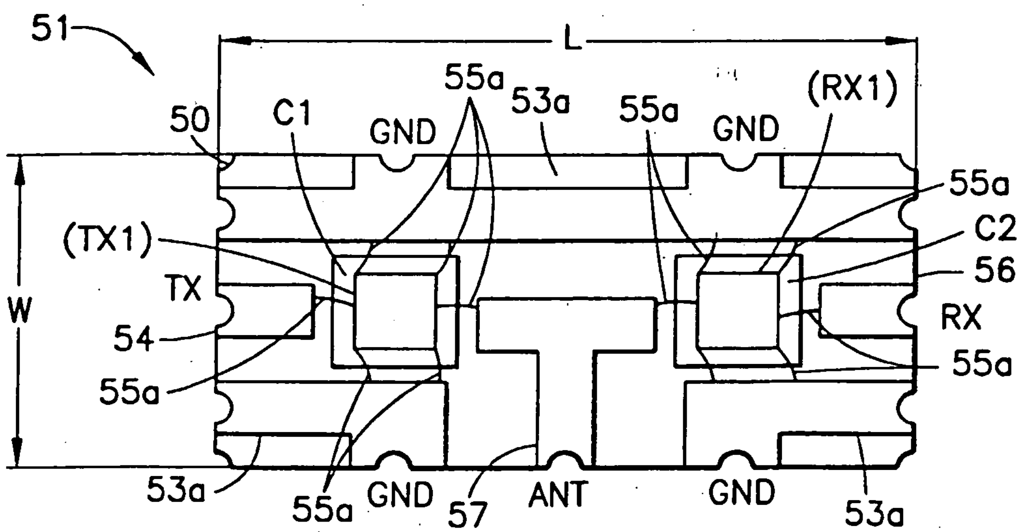


FIG.14a

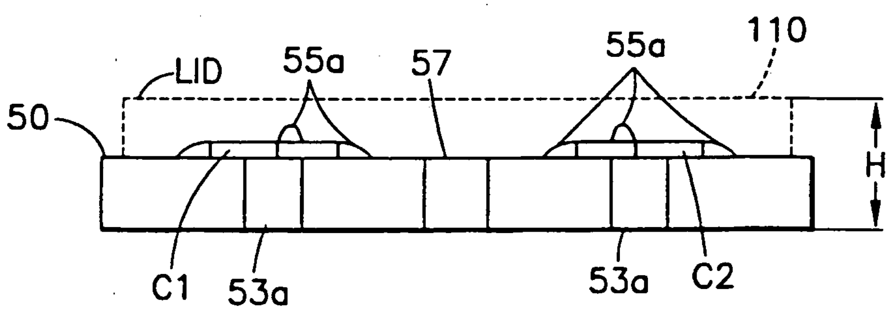


FIG.14b

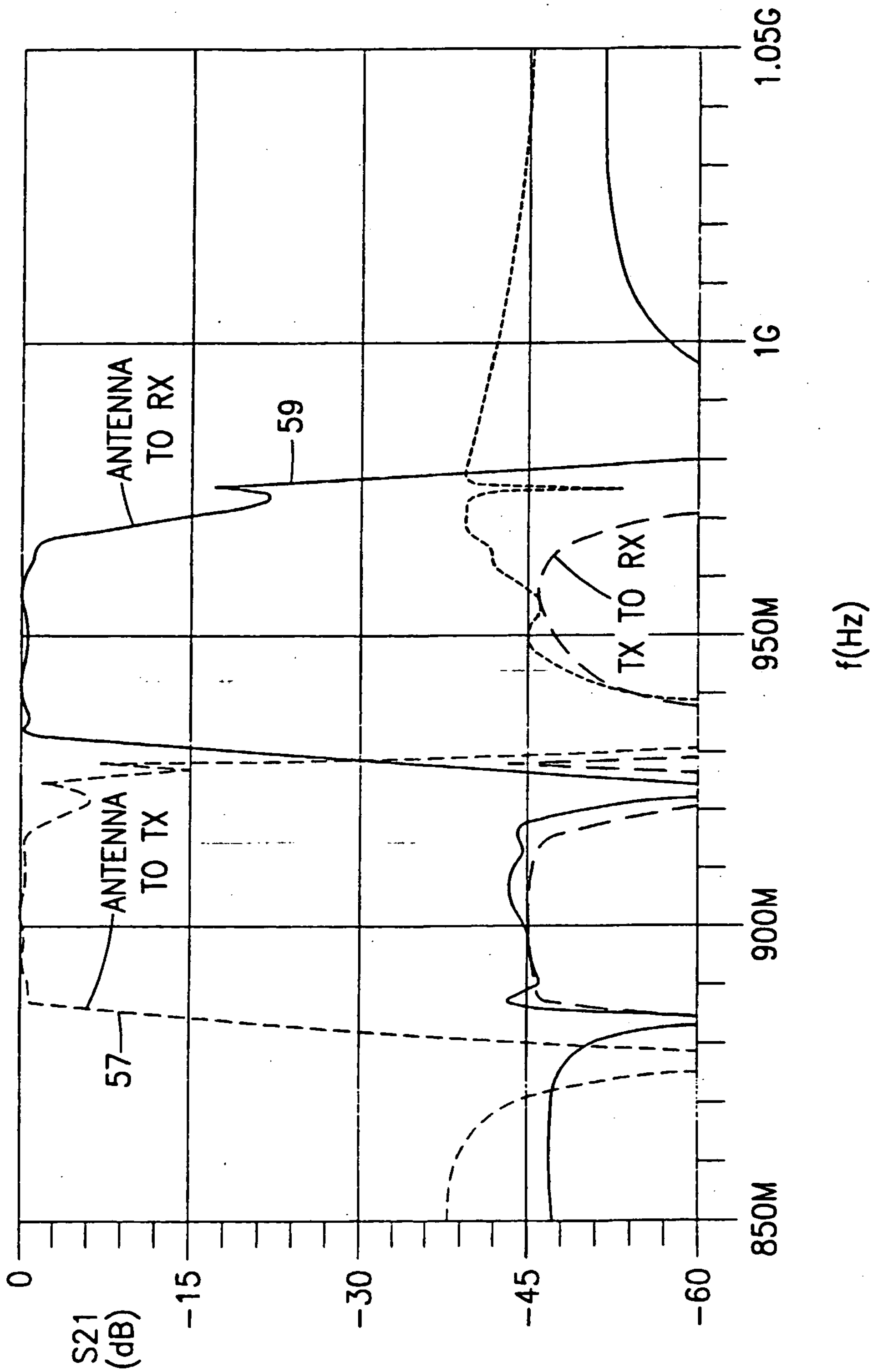

S21
(dB)
0
-15
-30
-45
-60
850M
900M
950M
1G
1.05G
f(Hz)
ANTENNA
TO TX
ANTENNA
TO RX
TX TO RX
57
59

FIG. 15

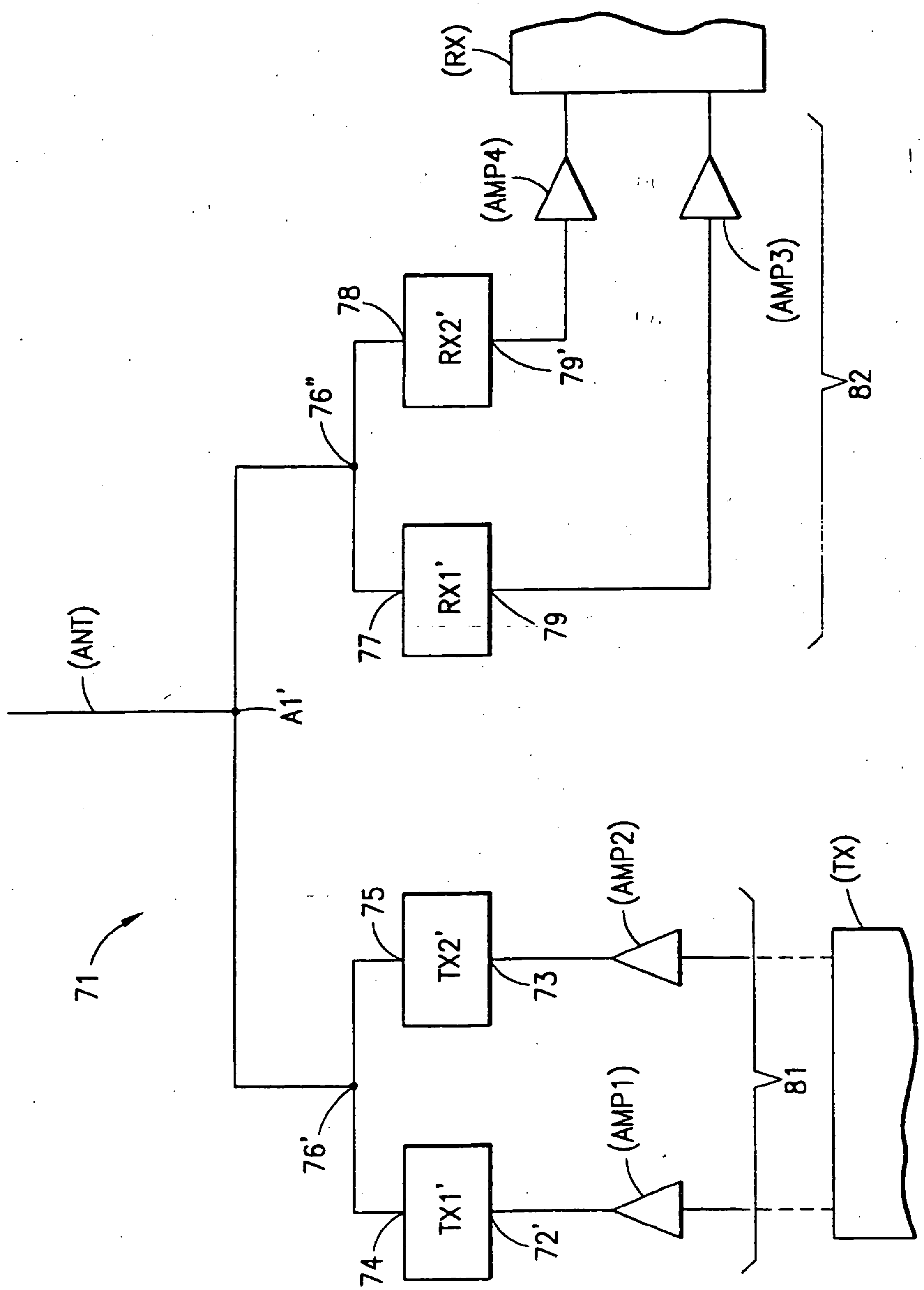

71
(ANT)
A1'
76"
76'
78
77
RX2'
RX1'
79'
79
(AMP4)
(AMP3)
(RX)
82
75
74
TX2'
TX1'
73
72'
(AMP2)
(AMP1)
(TX)
81

FIG.16

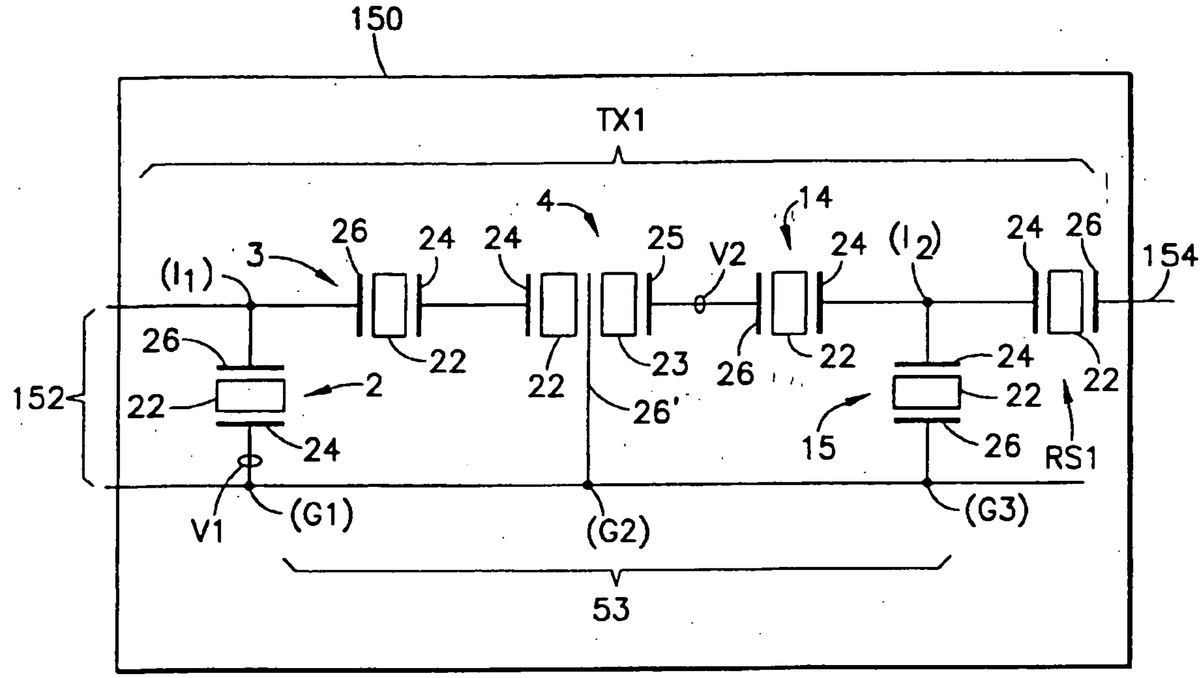


FIG.17a

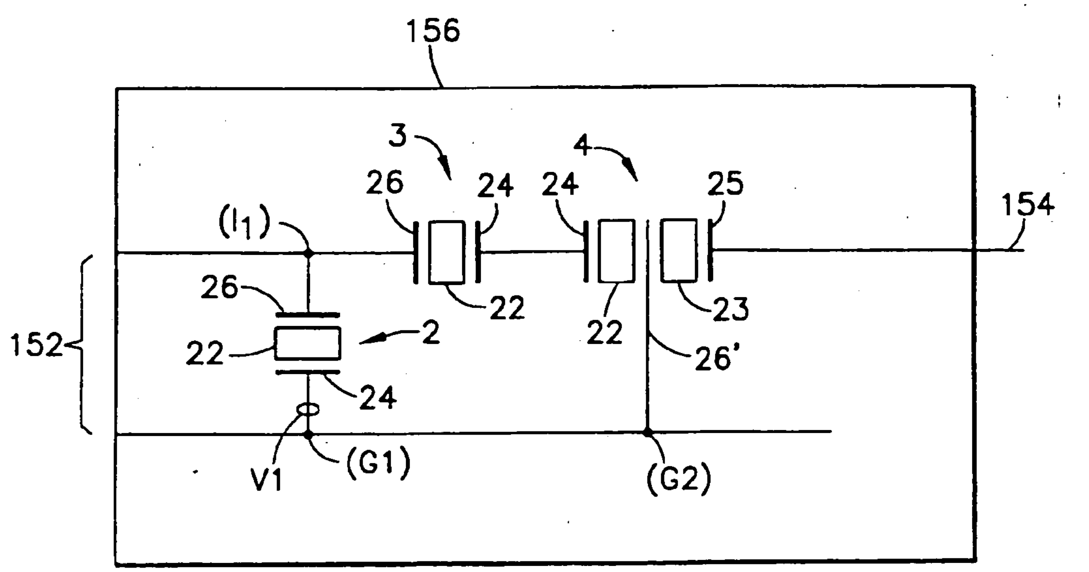


FIG.17b

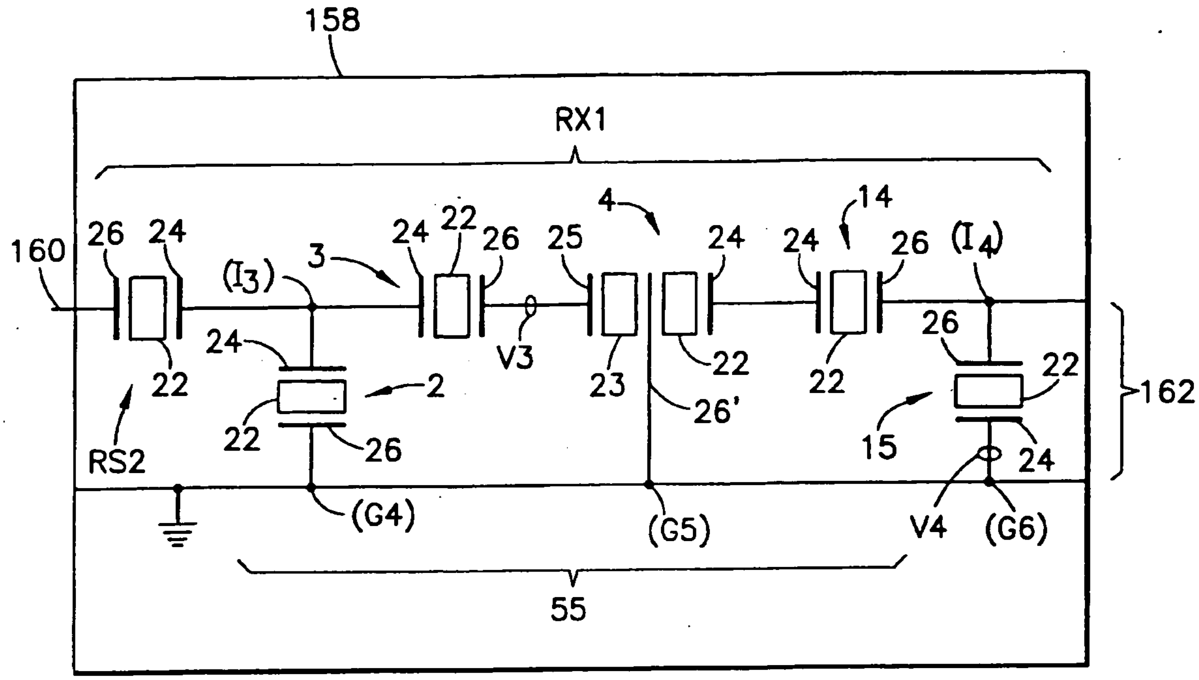


FIG.18a

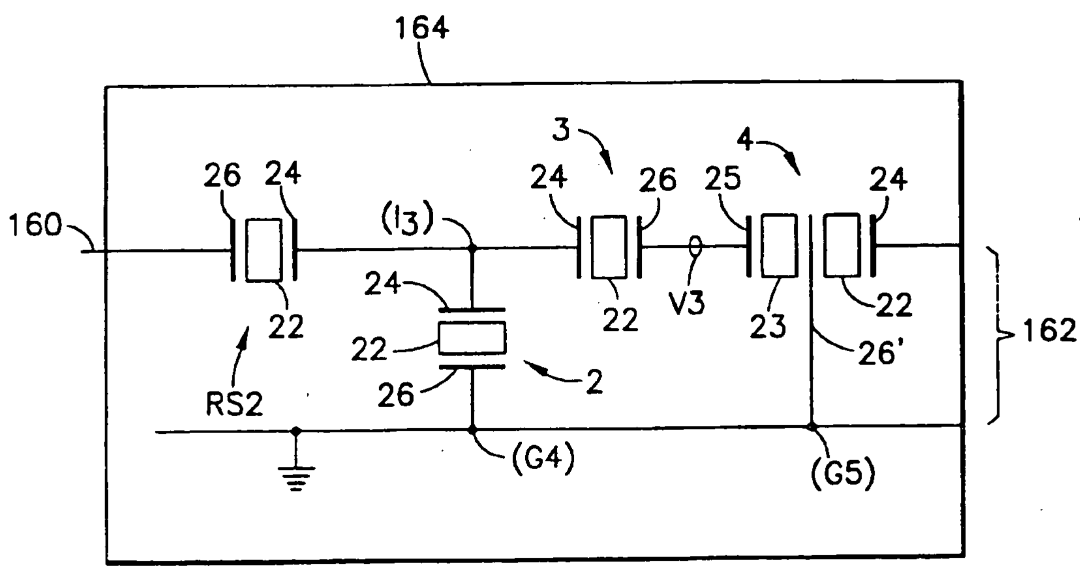


FIG.18b